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(54) **Whole blood centrifugal separation apparatus and method**

Vorrichtung und Verfahren zum Zentrifugaltrennen von Vollblut

Appareil et procédé pour la séparation centrifuge de sang total

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## Description

### Field of the Invention

[0001] The invention relates to a centrifugal processing apparatus and method.

### Background of the Invention

[0002] Today blood collection organizations routinely separate whole blood by centrifugation into its various therapeutic components, such as red blood cells, platelets, and plasma.

[0003] Conventional blood processing systems and methods use durable centrifuge equipment in association with single use, sterile processing chambers, typically made of plastic. The centrifuge equipment introduces whole blood into these chambers while rotating them to create a centrifugal field.

[0004] Whole blood separates within the rotating chamber under the influence of the centrifugal field into higher density red blood cells and platelet-rich plasma. An intermediate layer of white blood cells and lymphocytes forms an interface between the red blood cells and platelet-rich plasma.

[0005] In conventional blood separation systems and methods, platelets lifted into suspension in the PRP can settle back upon the interface. The platelets settle, because the radial velocity of the plasma undergoing separation is not enough to keep the platelets in suspension. Lacking sufficient radial flow, the platelets fall back and settle on the interface. This reduces processing efficiencies, lowering the effective yield of platelets.

[0006] The present invention provides, as set out in Claim 1, a method for centrifugally separating whole blood into red blood cells; plasma; and a platelet concentrate.

[0007] The present invention also provides a centrifugal separation apparatus as set out in Claim 5.

[0008] The invention provides improved blood processing apparatus and methods that create unique dynamic flow conditions within the processing chamber. These flow conditions continuously free platelets from the interface, sweeping them into the platelet-rich plasma stream for collection. The dynamic flow conditions also serve to maximise exposure of the blood components to the centrifugal separation forces, further enhancing separation efficiencies.

[0009] One embodiment of the invention provides a chamber and associated method for separating whole blood into red blood cells and a plasma constituent carrying platelets in a rotating field.

[0010] A separation zone is formed between first and second spaced apart walls. The separation zone includes an entry region, where whole blood enters the separation chamber to begin separation. The separation zone also includes a terminal region spaced from the entry region, where separation is halted.

[0011] Whole blood is conveyed through the separation zone from the entry region toward the terminal region. The separation of plasma constituent from the red blood cells successively increases the blood hematocrit along the flow path.

[0012] According to the invention, an outlet port collects the plasma constituent in the entry region of the separation zone, where blood hematocrit is the least. In other words, the plasma constituent is collected in the same region where whole blood enters the separation zone. The result is significantly higher yields of platelets.

[0013] The inventor has discovered that the initial separation of red blood cells toward the high-G wall in the entry region of the chamber creates a high radial flow of plasma. This high radial flow of plasma elutes platelets from the interface into suspension.

[0014] In a preferred embodiment, a fluid, such as plasma, is circulated into the entry region of the processing zone to reduce the hematocrit of the whole blood to a predetermined value. The inventor has discovered that this predetermined value maximizes the radial plasma flow in this region of the separation zone.

[0015] A preferred embodiment provides a second collection area for directing red blood cells from the entry region to a second outlet port for transporting red blood cells from the chamber.

### Brief Description of the Drawings

[0016]

Fig. 1 is a diagrammatic view of an enhanced yield axial flow processing chamber that illustrates some principles of the invention;

Fig. 2 is a diagrammatic view of the chamber shown in Fig. 1 operating in a centrifugation field;

Fig. 3 is a diagrammatic view of the interior of the chamber shown in Fig. 1 when processing whole blood within the centrifugation field;

Fig. 3A is a graph showing the distribution of increasing regions of surface hematocrit along the interface formed in a blood separation chamber;

Fig. 4 is a diagrammatic view of an enhanced yield circumferential flow processing chamber that embodies the features of the invention;

Fig. 5 is a diagrammatic view of the chamber shown in Fig. 4 operating in a centrifugation field;

Fig. 6 is a diagrammatic view of the interior of the chamber shown in Fig. 4 when processing whole blood within the centrifugation field;

Figs. 7 and 8 are diagrammatic views of prior art circumferential flow blood processing chambers;

Fig. 9 is a plan view of a blood processing assembly that incorporates an enhanced yield circumferential flow processing chamber that embodies the features of the invention;

Fig. 10 is a view of the interior of the blood processing assembly shown in Fig. 9, taken between the

low-G and high-G walls radially along the centrifugation field;

Fig. 11 is a plan view of an alternative blood processing assembly that incorporates an enhanced yield circumferential flow processing chamber that embodies the features of the invention;

Fig. 12 is a view of the interior of the blood processing assembly shown in Fig. 11, taken between the low-G and high-G walls radially along the centrifugation field;

Fig. 13 is a side view of a centrifuge that can be used in association with either one of the blood processing assemblies shown in Figs. 9/10 or 11/12, showing the bowl and spool assemblies in their upraised and separated position;

Fig. 14 is a side view of the centrifuge shown in Fig. 13, showing the bowl and spool assemblies in their suspended and operating position;

Fig. 15 is an enlarged perspective view of one of the blood processing assemblies shown in Figs. 9/10 or 11/12 being wrapped for use about the spool of the centrifuge shown in Fig. 13;

Fig. 16 is an enlarged perspective view, with portions broken away, of one of the blood processing assemblies shown in Figs. 9/10 or 11/12 mounted for use on the bowl and spool assemblies of the centrifuge shown in Fig. 13;

Fig. 17 is a top interior section view, taken generally along line 17-17 in Fig. 16, of the processing chamber formed by the bowl and spool assemblies of the centrifuge shown in Fig. 13;

Figs. 18A/B/C are enlarged perspective views of an interior ramp used in association with either one of the blood processing assemblies shown in Figs. 9/10 or 11/12 for controlling flow of PRP from the chosen assembly;

Fig. 19 is a view of the vortex conditions generated within the blood processing assembly shown in Figs. 9/10 during use;

Fig. 20 is a single needle platelet collection system that can be used in association with either one of the blood processing assemblies shown in Figs. 9/10 or 11/12;

Fig. 21 is a double needle platelet collection system that can be used in association with either one of the blood processing assemblies shown in Figs. 9/10 or 11/12;

Fig. 22 is a plasma recirculation control system that can be used in association with either one of the blood processing systems shown in Figs. 20 or 21; Fig. 23 is a perspective view, with portions broken away and in section, of an interface control system mounted on the rotating (one omega) portion of the centrifuge shown in Figs. 13 and 14 and used in association with the ramp shown in Fig. 18;

Fig. 24A is an enlarged perspective view of the rotating interface viewing head associated with the interface control system shown in Fig. 23;

Fig. 24B is a side section view showing the interior of rotating interface viewing head shown in Fig. 24A;

Fig. 25 is a schematic view of the light intensity control circuit associated with the interface control system shown in Fig. 23;

Figs. 26A/B/C are a series of diagrammatic views showing the operation of the interface control system shown in Fig. 23 during rotation of the centrifuge assembly;

Figs. 27A/B are flow charts showing the operation of the interface control circuit associated with the interface control system shown in Fig. 23;

Figs. 28A/B show, respectively, the platelet counts and mean platelet volumes sampled during a 45 minute procedure using a separation chamber that embodies the features of the invention; and

Figs. 29A/B show, respectively, the platelet counts and mean platelet volumes sampled during a 45 minute procedure using another separation chamber than embodies the features of the invention.

## Description of the Preferred Embodiments

### I. ENHANCED YIELD AXIAL FLOW SYSTEMS

#### Single Stage Whole Blood Separation Systems

[0017] Figs. 1 to 3 show, in diagrammatic fashion, a single stage axial flow centrifugal blood processing system. The arrangement of Figures 1 to 3 does not form part of the invention as claimed herein. Nonetheless Figures 1 to 3 are illustrative of principles employed in the invention. The system includes a chamber 10.

[0018] In use, the system separates whole blood within the chamber 10 into red blood cells (RBC) and plasma rich in platelets (called platelet-rich plasma, or PRP). This specification and drawings will identify red blood cells as RBC; platelet-rich plasma as PRP; and whole blood as WB.

[0019] The system includes a holder 12 that rotates the chamber 10 about an axis 14 (see Fig. 2), to thereby create a centrifugal field within the chamber 10. The centrifugal field extends from the rotational axis 14 radially through the chamber 10.

[0020] As Fig. 3 shows, the chamber wall 16 closest to the rotational axis 14 will be subject to a lower centrifugal force (or G-force) than the chamber wall 18 farthest away from the rotational axis 14. Consequently, the closer chamber wall 16 will be called the low-G wall, and the farthest chamber wall 18 will be called the high-G wall.

[0021] While rotating, the chamber 10 receives WB through a first port 20. The WB follows an axial flow path in the chamber 10. That is, it flows in a path that is generally parallel to the rotational axis 14 (as Fig. 2 best shows). Consequently, the chamber 10 will be called an axial flow blood processing chamber.

**[0022]** In the geometry shown in Figs. 1 and 2, the transverse top and bottom edges of the axial flow chamber 10 (which lie across the axial flow path) are shorter than the longitudinal side edges (which lie along the axial flow path). Still, alternative geometries are possible. For example, the transverse top and bottom edges can extend 360 degrees to form a bowl, the outer periphery of which constitutes an axial flow chamber.

**[0023]** WB separates within the chamber 10 under the influence of the centrifugal field into RBC and PRP. As Fig. 3 shows, the higher density RBC move toward the high-G wall 18, displacing the lighter density PRP toward the low-G wall 16. A second port 22 draws the RBC from the chamber 10 for collection. A third port 24 draws the PRP from the chamber 10 for collection.

**[0024]** An intermediate layer called the interface 26 forms between the RBC and PRP. The interface 26 constitutes the transition between the formed cellular blood components and the liquid plasma component. Large amounts of white blood cells and lymphocytes populate the interface 26.

**[0025]** Platelets, too, can leave the PRP and settle on the interface 26. This settling action occurs when the radial velocity of the plasma near the interface 26 is not enough to keep the platelets suspended in the PRP. Lacking sufficient radial flow of plasma, the platelets fall back and settle on the interface 26.

**[0026]** One aspect of the invention establishes flow conditions within the chamber 10 to "elute" platelets from the interface 26 in an apparatus, described below, that differs from the apparatus of Figures 1 to 3. The elution lifts platelets from the interface 26 and into suspension in the PRP.

**[0027]** To establish beneficial elution conditions within the chamber 10, the PRP collection port 24 and the WB inlet port 20 are juxtaposed so that the PRP exits the chamber 10 in the same region where WB enters the chamber 10.

**[0028]** The Fig. 1 arrangement locates the PRP collection port 24 on the same transverse edge of the chamber 10 as the WB inlet port 20. In Figs. 1 to 3, this transverse edge is located physically at the top of the chamber 10.

**[0029]** The RBC collection port 22 and the PRP collection port 24 are arranged so that PRP exits the chamber 10 in a region opposite to the region where RBC exit the chamber 10, relative to the axial flow of WB in the chamber 10.

**[0030]** The Fig. 1 arrangement locates the RBC collection port 22 on the transverse edge that is opposite to transverse edge where the WB inlet and PRP collection ports 20 and 24 are located. In Figs. 1 to 3, this transverse edge is located physically at the bottom of the chamber 10.

**[0031]** It should be appreciated that the centrifugal field is not sensitive to "top" and "bottom" port placement. The particular "top edge" and "bottom edge" relationship of the ports 20; 22; and 24 shown in Figs. 1

to 3 could be reversed, placing the WB inlet and PRP collection ports 20 and 24 on the bottom edge and the RBC collection port 22 on the top edge.

**[0032]** To further enhance the platelet elution conditions within the chamber 10, the distance between the low-G wall 16 and the interface 26 is preferably smaller in the region of the RBC collection port 22 than in the region of the PRP collection port 24. The Fig. 1 arrangement (see Fig. 3) achieves this result by uniformly tapering the low-G wall 16 toward the high-G wall 18 between the PRP collection port 24 and the RBC collection port 22. Fig. 3 shows the tapering low-G wall 16 in phantom lines.

**[0033]** The same result can be obtained without continuously or uniformly tapering the low-G wall 16 along the entire length of the axial flow path between the PRP collection port 24 and the RBC collection port 22. The low-G wall 16 can begin its taper farther away from the PRP collection port 24 than Fig. 3 shows, closer to the region of the RBC collection port 22.

**[0034]** The axial flow processing chamber 10 serves to increase platelet yields due to the interplay of two principal dynamic flow conditions, one radial and the other axial in direction.

**[0035]** First, due to the juxtaposition of the WB inlet port 20 and the PRP collection port 24, the chamber 10 produces a dynamic radial plasma flow condition near the PRP collection port 24. The radial flow condition is generally aligned along the centrifugal force field. The radial plasma flow condition continuously elutes platelets off the interface 26 into the PRP flow next to the PRP collection port 24.

**[0036]** Second, by narrowing the gap between the low-G wall 16 and the interface 26 next to the RBC collection port 22, compared to the gap next to the PRP collection port 24, the chamber 10 produces a dynamic axial plasma flow condition between the two ports 22 and 24. The axial flow condition is generally transverse the centrifugal force field. The axial plasma flow condition continuously drags the interface 26 back towards the PRP collection port 24, where the higher radial plasma flow conditions exist to sweep the platelets off the interface 26.

**[0037]** Fig. 3 diagrammatically shows the enhanced platelet separation effect due to these complementary radial and axial flow conditions.

**[0038]** WB enters the chamber 10 at a given entry hematocrit, which indicates the volume of RBC per unit volume of WB. A typical healthy donor has a predonation hematocrit of about 42.5%.

**[0039]** The hematocrit of the blood lying on the boundary between the RBC and plasma along the interface 26 (called the surface hematocrit) remains at or substantially the same as the entry hematocrit in the entry region  $R_c$  of the chamber 10 near the WB inlet port 20. Fig. 3A shows this entry region  $R_c$  as lying to the left of the 0.40 surface hematocrit isoconcentration line (which is the same as the entry 40% hematocrit).

**[0040]** The size of the entry region  $R_c$  varies according to the hematocrit of the blood entering the chamber 10. For a given chamber configuration, the lower the entry hematocrit is, the smaller the entry region  $R_c$  becomes.

**[0041]** The size of the entry region  $R_c$  also depends upon the strength of the centrifugal field within the chamber and the surface area of the chamber.

**[0042]** As Fig. 3A shows, the surface hematocrit successively increases above its entry level outside the entry region  $R_c$  along the length of the chamber 10 toward the terminal region  $R_t$ , where separation is halted. This is because more red blood cells separate and collect toward the high-G wall 18 along the length of the chamber 10.

**[0043]** Fig. 3A shows the increasing surface hematocrit along the interface 26 as intersected by isoconcentration lines 0.6 (representing a 60% surface hematocrit) to 0.9 (representing a 90% surface hematocrit).

**[0044]** Further details of the distribution of RBC during centrifugation in a chamber are set forth in Brown, "The Physics of Continuous Flow Centrifugal Cell Separation," *Artificial Organs*, 13(1):4-20 (1989), from which Fig. 3A is taken.

**[0045]** As Fig. 3A shows, the surface hematocrit is least in the entry region  $R_c$  of the chamber 10 near the WB inlet port 20. As Fig. 3 shows, the velocity at which the RBC settle toward the high-G wall 18 in response to centrifugal force is greatest in the entry region  $R_c$ . Because the surface hematocrit is the least, there is more plasma volume to displace in the entry region  $R_c$ .

**[0046]** This, in turn, increases the radial velocity at which plasma is displaced by the separating RBC mass in response to the centrifugal force field. As the RBC mass moves toward the high-G wall 18, the plasma is displaced in a radial flow path toward the low-G wall 16. As a result, relatively large radial plasma velocities occur in the entry region  $R_c$ .

**[0047]** These large radial velocities toward the low-G wall 16 elute large numbers of platelets from the RBC mass. As a result, fewer platelets remain entrapped on the interface 26 here than elsewhere in the chamber 10.

**[0048]** The purposeful arrangement of the ports 20; 22; and 24 in the separation chamber 10 also contributes to further enhanced elution of platelets. The WB inlet port 20 is diametrically spaced from the RBC collection port 22, but the WB inlet port 20 is alongside the PRP collection port 24. This isolation between the WB inlet port 20 and the RBC collection port 22 forces the RBC to traverse the entire axial length of the chamber 10 during processing. This maximizes its exposure to the centrifugal force field.

**[0049]** The isolation between the RBC collection port 22 and the PRP collection port 24 directs the RBC toward the RBC collection port 22. At the same time, it directs the PRP stream in the opposite direction toward the PRP collection port 24.

**[0050]** Furthermore, due to the displaced low-G wall

16, the distance between the low-G wall 16 and the interface 26 increases between the region of the RBC collection port 22 and the PRP collection port 24. As a result, the plasma layer along the interface 26 increases in radial depth in the intended direction of PRP flow, i. e., away from the RBC collection port 22 and toward the axially spaced PRP collection port 24. The plasma near the RBC collection port 22 is closer to the high-G centrifugation field than the plasma near the PRP collection port 24.

**[0051]** This shift in the relative position of the plasma between the two ports 22 and 24 causes the lighter plasma to move along the interface 26. The plasma moves swiftly away from the relatively more confined region closer to the high-G field (i. e., next to the RBC collection port 22), toward the relatively more open region closer to the low-G field (i. e., next to the PRP collection port 24).

**[0052]** This swiftly moving axial plasma flow actually drags the interface 26 -- and platelets entrapped within it -- continuously toward the PRP collection port 24. There, the radial plasma velocities are the greatest to supply the greatest elution effect, lifting the entrapped platelets free of the interface 26 and into the PRP stream for collection through the port 24.

**[0053]** The close juxtaposition of the WB inlet port 20 and the PRP collection port 24 will alone result in improved platelet elutriation in the chamber 10, without altering the radial position of the low-G wall 16 relative to the interface 26. The enhanced radial flow conditions will alone keep the majority of the platelet population in suspensions in the PRP for collection.

**[0054]** The remaining minority of the platelet population constitutes platelets that are physically larger. These larger platelets typically occupy over  $15 \times 10^{-15}$  liter per platelet (femtoliters, or cubic microns), and some are larger than 30 femtoliters. In comparison, most platelets average about 8 to 10 femtoliters (the smallest of red blood cells begin at about 30 femtoliters).

**[0055]** These larger platelets settle upon the interface 26 quicker than most platelets. These larger platelets are most likely to become entrapped in the interface 26 near the RBC collection port 22.

**[0056]** The axial plasma flow conditions established along the interface 26 by the displaced low-G wall 16 moves these larger, faster settling platelets with the interface 26. The axial plasma flow moves the larger platelets toward the PRP collection port 24 into the region of high radial plasma flow. The high radial plasma flow lifts the larger platelets from the interface 26 for collection.

**[0057]** The complementary flow conditions continuously lift platelets of all sizes from the interface 26 next to the PRP collection port 24. They work to free platelets of all sizes from the interface 26 and to keep the freed platelets in suspension within the PRP.

**[0058]** Simultaneously (as Fig. 3 shows), the counter-flow patterns serve to circulate the other heavier components of the interface 26 (the lymphocytes, mono-

cytes, and granulocytes) back into the RBC mass, away from the PRP stream.

**[0059]** As a result, the PRP exiting the PRP collection port 24 carries a high concentration of platelets and is substantially free of the other blood components.

## **II. ENHANCED YIELD CIRCUMFERENTIAL FLOW CHAMBERS**

**[0060]** The principles of the invention previously described in the context of an axial flow blood separation chamber can be employed in providing a circumferential flow blood processing chamber, according to the invention, with enhanced platelet separation efficiencies.

**[0061]** Figs. 4 to 6 show, in diagrammatic fashion, a circumferential flow centrifugal blood processing chamber 58 that embodies the features of the invention.

**[0062]** In use, the chamber 58 rotates on a rotor 60 about an axis 62 (see Fig. 5), to thereby create a centrifugal field within the chamber 58. Just as with the axial flow chamber 10 shown in Figs. 1 to 3, the centrifugal field extends radially from the axis through the chamber 58. As Fig. 13 shows, the chamber wall 64 closest to the axis constitutes the low-G wall, and the chamber wall 66 farthest from the axis constitutes the high-G wall.

**[0063]** While rotating, the chamber 58 receives WB through a first port 68. The WB follows a circumferential flow path in the chamber 58; that is, it flows in a circumferential path about the rotational axis 62 (as Fig. 5 best shows). For this reason, the chamber 58 is called a circumferential flow blood processing chamber.

**[0064]** In this geometry, the transverse top and bottom edges of the chamber 58 (which lie along the circumferential flow path) are usually longer than the longitudinal side edges (which lie across the circumferential flow path). The circumferential flow chamber 58 usually forms the shape of a tube that is elongated in the direction of rotation. Still, other configurations defining a circumferential flow path can be used.

**[0065]** WB separates within the tubular chamber 58 under the influence of the centrifugal field into RBC and PRP. As Fig. 6 shows, the higher density RBC move toward the high-G wall 66, displacing the lighter density PRP toward the low-G wall 64. The interface 26 (previously described) forms between them. A second port 70 draws the RBC from the chamber 58 for collection. A third port 72 draws the PRP from the chamber 58 for collection.

**[0066]** According to the invention, the PRP collection port 72 and the WB inlet port 68 are juxtaposed so that the PRP exits the circumferential flow chamber 58 in the same region where WB enters the chamber 58. In the illustrated embodiment, as shown in Fig. 4, the PRP collection port 72 is located along the same longitudinal side edge of the circumferential flow chamber 58 as the WB inlet port 68.

**[0067]** Also the RBC collection port 70 and the PRP collection port 72 are arranged so that PRP exits the

chamber 58 in a region opposite to the region where RBC exit the chamber 58, relative to the circumferential flow of WB in the chamber 58. In the illustrated embodiment, as Fig. 4 shows, the RBC collection port 70 is located on the longitudinal side edge that is opposite to the longitudinal side edge where the WB inlet and PRP collection ports are located.

**[0068]** The chamber 58 shown in Figs. 4 to 6 differs significantly from prior circumferential flow blood separation chambers 58A and 58B, which are shown in Figs. 7 and 8. The prior circumferential flow chambers 58A/B purposely located the PRP collection port 72 away from the WB inlet port 68.

**[0069]** In the prior circumferential flow chamber 58A shown in Fig. 7, the PRP collection port 72 occupies one side edge, diametrically opposite to the RBC collection port 70, which occupies the other side edge. In this construction, the WB inlet port 68 is located in a side wall of the chamber 58A between the two side edges.

**[0070]** In the prior circumferential flow chamber 58B shown in Fig. 8, the PRP collection port 72 occupies one side edge, while the WB inlet port 68 and the RBC outlet port occupy the opposite side edge, oppositely spaced away from the PRP collection port 72 relative to the circumferential flow of WB in the chamber 58B.

**[0071]** In both the Fig. 7 construction and the Fig. 8 construction, no ports are located on the top and bottom transverse edges of the chamber 58B. Neither chamber 58A and 58B has a port with an axis that extends parallel to the axis of rotation.

**[0072]** Fig. 6 diagrammatically shows the enhanced platelet separation effect due to the adjacent positions of the WB inlet port 68 and the PRP collection port 72 in the circumferential flow chamber 58 that embodies the invention. The effect is generally the same as that shown in Fig. 3, except the chamber 58 is oriented differently to establish the circumferential flow pattern.

**[0073]** As Fig. 6 shows, the PRP collection port 72 draws PRP from the chamber 58 where velocity at which the RBC settle toward the high-G wall 66 in response to centrifugal force is the greatest, i.e., next to the WB inlet port 68. Here, too, is where the radial plasma velocity is the greatest to lift platelets from the interface 26, and to keep them in suspension within the plasma for transport out via the PRP collection port 72.

**[0074]** The WB inlet port 68 is oppositely spaced from the RBC collection port 70 (in the circumferential flow direction), forcing the RBC to traverse the entire axial length of the chamber 58, thereby maximizing their exposure to the centrifugal separation forces. The isolation between the RBC collection port 70 and the PRP collection port 72 also directs the RBC toward the RBC collection port 70, while directing the PRP stream in the opposite direction toward the PRP collection port 72.

**[0075]** Like the chamber 10 shown in Fig. 3, the low-G wall 64 is preferably displaced inward toward the interface 26 near the RBC collection port 70. As a result, the radial distance between the low-G wall 64 and inter-

face 26 is greater near the PRP collection port 72 than near the RBC collection port 70.

[0076] As previously described with reference to Fig. 3, the displaced low-G wall 64 causes the lighter plasma to move along the interface 26 swiftly away from the relatively more confined region next to the RBC collection port 70, toward the relatively more open region next to the PRP collection port 72. The same beneficial effect results: the circumferential plasma flow drags the interface 26 -- and larger, faster settling platelets entrapped within it -- continuously toward the PRP collection port 72, where the radial plasma velocities are the greatest to supply the greatest elution effect. The counterflow patterns also serve to circulate the other heavier components of the interface (lymphocytes, monocytes, and granulocytes) back into the RBC mass, away from the PRP stream.

[0077] As Fig. 6 shows, the low-G wall 64 continuously tapers in the direction of the circumferential flow path, e.g., away from the PRP collection port 72 and in the direction of axial flow path of the WB. The same result can be obtained without continuously or uniformly tapering the low-G wall 16 along the entire length of the axial flow path between the PRP collection port 72 and the RBC collection port 70. The low-G wall 16 can begin its taper farther away from the PRP collection port 24 than Fig. 6 shows, closer to the region of the RBC collection port 70.

[0078] The circumferential flow chamber 58 that embodies the invention can be variously constructed. Figs. 9 and 10 show the physical construction of one preferred circumferential flow chamber assembly 74 that embodies the features of the invention. Figs. 18 and 19 show the physical construction of an alternative circumferential flow assembly 76.

[0079] Either assembly 74 or 76 can be used in association with a blood processing centrifuge 78, like that shown in Figs. 11 and 12. Further details of this centrifuge construction are set forth in EP-A-0572656.

[0080] As Fig. 13 shows, the centrifuge 78 includes a bowl element 80 and a spool element 82. The bowl and spool elements 80 and 82 can be pivoted on a yoke 85 between an upright position, as Fig. 13 shows, and a suspended position, as Fig. 14 shows.

[0081] When upright, the bowl and spool elements 80 and 82 are presented for access by the user. A mechanism permits the spool and bowl elements 80 and 82 to assume a mutually separated position, as Fig. 13 shows. In this position, the spool element 80 is at least partially out of the interior area of the bowl element 82 to expose the exterior spool surface for access. As Fig. 15 shows, when exposed, the user can wrap either circumferential flow chamber assembly 74 or 76 about the spool element 82.

[0082] The mechanism also permits the spool and bowl elements 80 and 82 to assume a mutually cooperating position, as Fig. 16 shows. In this position, the spool element 82 and the chosen circumferential flow

chamber assembly 74 or 76 are enclosed within the interior area of the bowl element 80, as Fig. 16 shows. A processing chamber 83 is formed between the interior of the bowl element 80 and the exterior of the spool element 82. The chosen circumferential flow chamber assembly 74 or 76 is carried with and assumes the contours of the processing chamber 83.

[0083] When closed, the spool and bowl elements 80 and 82 can be pivoted as an assembly into a suspended position, as Fig. 14 shows. When suspended, the bowl and spool elements 80 and 82 are in position for operation. In operation, the centrifuge 78 rotates the suspended bowl and spool elements 80 and 82 about an axis.

[0084] In the illustrated embodiments, each circumferential flow chamber assembly 74 and 76 provides multi-stage processing. A first stage separates RBC and PRP from WB. A second stage separates PC and PPP from the PRP.

[0085] While the interior of either circumferential flow chamber assembly 74 or 76 can be variously arranged, Figs. 9/10 and 11/12 show the interior of the alternative circumferential flow chambers divided into two side-by-side processing compartments 84 and 86. In use, centrifugal forces in the first compartment 84 separate whole blood into RBC and PRP. Centrifugal forces in the second processing compartment 86 separate the PRP from the first stage into PC and PPP.

[0086] In both alternative circumferential flow chambers, a first peripheral seal 88 forms the outer edge of the circumferential flow chamber assembly 74 or 76. A second interior seal 90 divides the circumferential flow chamber assembly 74 or 76 into the first processing compartment 84 and the second processing compartment 86. The second seal 90 extends generally parallel to the rotational axis of the chamber assembly 74 or 76; that is, it extends across the circumferential flow of the chamber assembly 74 or 76. The second seal 90 constitutes a longitudinal edge common to both first and second processing compartments 84 and 86.

[0087] Each processing compartment 84 and 86 serves as a separate and distinct separation chamber and will therefore be referred to as such.

[0088] In each alternative circumferential flow chambers, five ports 92/94/96/98/100 open into the compartmentalized areas formed in the processing chamber assembly 74 or 76. The ports 92/94/96/98/100 are arranged side-by-side along the top transverse edge of the respective chamber 84 and 86.

[0089] The ports 92/94/96/98/100 are all axially oriented; that is, their axes are aligned with the axis of rotation, transverse the circumferential fluid flow path within the chamber assembly 74 or 76 itself. Three ports 92/94/96 serve the first chamber 84. Two ports 98/100 serve the second chamber 86.

[0090] In both alternative circumferential flow chamber assemblies 74 and 76, an umbilicus 102 (see Fig. 17) attached to the ports 92/94/96/98/100 interconnects



the first and second chambers 84 and 86 with each other and with pumps and other stationary components located outside the rotating components of the centrifuge 78.

[0091] As Fig. 14 shows, a non-rotating (zero omega) holder 104 holds the upper portion of the umbilicus 102 in a non-rotating position above the suspended spool and bowl elements 80 and 82. A holder 106 on the yoke 85 rotates the mid-portion of the umbilicus 102 at a first (one omega) speed about the suspended spool and bowl elements 80 and 82. Another holder 108 (see Fig. 15) rotates the lower end of the umbilicus 102 at a second speed twice the one omega speed (the two omega speed), at which the suspended spool and bowl elements 80 and 82 also rotate. As before stated, this known relative rotation of the umbilicus keeps it untwisted, in this way avoiding the need for rotating seals.

[0092] Using either alternative circumferential flow chamber assembly 74 or 76, the two omega speed at which the suspended spool and bowl elements 80 and 82 rotate is about 3400 RPM. Given the dimensions of the spool and bowl elements 80 and 82, 3400 RPM will develop a centrifugal force field of about 900 G's along the high-G wall 66 of the chambers 84 and 86.

#### A. The First Stage Processing Chamber

[0093] In the embodiment shown in Figs. 9 and 10, the first port 92 comprises the previously described PRP collection port (identified by reference numeral 72, as in Figs. 4 to 6). The second port 94 comprises the previously described WB inlet port (identified by reference numeral 68, as in Figs. 4 to 6). The third port 96 comprises the previously described RBC collection port (identified by reference numeral 70, as in Figs. 4 to 6).

[0094] A third interior seal 110 is located between the PRP collection port 72 and the WB inlet port 68. The third seal 110 includes a first region 112 that is generally parallel to the second interior seal 90, thereby extending across the circumferential WB flow path. The third interior seal 110 then bends in a dog-leg portion 114 away from the WB inlet port 68 in the direction of circumferential WB flow. The dog-leg portion 114 terminates beneath the inlet of the PRP collection port 72.

[0095] A fourth interior seal 116 is located between the WB inlet port 68 and the RBC collection port 74. The fourth seal 116 includes a first region 118 that is generally parallel to the second and third interior seals 90 and 110, thereby extending across the circumferential WB flow path. The fourth interior seal 116 then bends in a dog-leg portion 120 away from the RBC collection port 74 in the direction of circumferential WB flow. The dog-leg portion 120 extends beneath and beyond the dog-leg portion 114 of the third seal 110. It terminates near the longitudinal side edge of the first chamber 84 that is opposite to the longitudinal side edge formed by the second interior seal 90.

[0096] Together, the third and fourth interior seals 110/116 form a WB inlet passage 122 that first extends

along the axis of rotation (i.e., between the first regions 112/118 of the two seals 110/116). The WB inlet passage 122 then bends to open in the direction of intended circumferential flow within the first chamber 84 (i.e., between the dog-leg portions 114/120 of the two seals 110/116).

[0097] The WB inlet passage 122 first channels WB away from the WB inlet port 68 in an axial flow path. It then channels WB circumferentially, directly into the circumferential flow path, where separation into RBC and PRP begins.

[0098] The third interior seal 110 also forms a PRP collection region 124 within the first chamber 84 (i.e., between the third seal 110 and the adjacent upper portion of the first peripheral seal 88).

[0099] Together, the fourth interior seal 116, the second interior seal 90, and the lower regions of the first peripheral seal 88 form a RBC collection passage 126 that extends first along the axis of rotation (i.e., between the second interior seal 90 and the fourth interior seal 116). The RBC collection passage 126 then bends in a circumferential path to open near the end of the intended WB circumferential flow path (i.e., between the dog-leg portion 120 of the fourth seal 116 and the lower region of the peripheral seal 88).

[0100] In the embodiment shown in Figs. 11 and 12, the first port 92 comprises the RBC collection port (identified by reference numeral 70, as in Figs. 4 to 6). The second port 94 comprises the PRP collection port (identified by reference numeral 72, as in Figs. 4 to 6). The third port 96 comprises the WB inlet port (identified by reference numeral 68, as in Figs. 4 to 6).

[0101] As Fig. 11 shows, a third interior seal 110 is located between the PRP collection port 72 and the WB inlet port 68. The seal 110 includes a first region 112 that is generally parallel to the second interior seal 90. It then bends in a dog-leg portion 114 away from the WB inlet port 68 in the direction of circumferential WB flow. The dog-leg portion 114 terminates beneath the inlet of the PRP collection port 72.

[0102] Together, the second and third interior seals 90 and 110 form a WB inlet passage 122, like the WB inlet passage 122 associated with the chamber 84 shown in Fig. 16, except in a different location within the chamber.

[0103] As Fig. 11 shows, a fourth interior seal 116 is located between the PRP collection port 72 and the RBC collection port 74. The fourth seal 116 includes a first region 118 that is generally parallel to the second and third interior seals 90 and 110, thereby extending across the circumferential flow path. The fourth interior seal 116 then bends in a dog-leg portion 120 away from the PRP collection port 72 in the direction of circumferential WB flow. It terminates near the longitudinal side edge of the first chamber 84 that is opposite to the longitudinal side edge formed by the second interior seal 90.

[0104] Together, the fourth interior seal 116 and the upper regions of the first peripheral seal 88 form a RBC collection passage 126, like the RBC collection passage



126 shown in Fig. 16, except that it is located at the top of the chamber 84, instead of at the bottom.

**[0105]** As Fig. 11 shows, the third and fourth interior seals 110 and 116 together also form a PRP collection region 124 within the first chamber, like the PRP collection region 124 shown in Fig. 9.

**[0106]** The dynamic flow conditions within each alternative circumferential flow chamber assembly 74 or 76 are the same. These conditions direct PRP toward the PRP collection region 124 for collection through the inlet of the PRP collection port 72.

**[0107]** As Figs. 9 and 11 show, the WB inlet passage 122 channels WB directly into the circumferential flow path immediately next to the PRP collection region 124. Here, the radial flow rates of plasma are greatest to lift platelets free of the interface and into the PRP collection region 124.

**[0108]** The RBC collection passage 126 receives RBC at its open end and from there channels the RBC to the RBC collection port 74. As Figs. 9 and 11 show, the WB inlet passage 122 channels WB directly into the flow path at one end of the first chamber 84, and the RBC collection passage 126 channels RBC out at the opposite end of the flow path.

**[0109]** In each alternative circumferential flow chamber assembly 74 and 76 (as Figs. 10 and 12 respectively show), the low-G wall 64 of the first chamber 84 is offset toward the high-G wall 66 near the RBC collection region.

**[0110]** In the particular embodiments shown, the low-G wall 64 tapers into the chamber 84 in the direction of circumferential WB flow. The taper proceeds from the second interior seal 90 toward the opposite longitudinal end of the chamber. Fig. 6 shows the tapering low-G wall 64 from another perspective.

**[0111]** The tapering low-G wall 64 includes a stepped-up barrier 128 or dam in the region where the RBC collection passage 126 opens. As Figs. 9 and 11 show for their respective chamber assembly, the stepped-up barrier 128 extends from the low-G wall 64 across the entire chamber 84.

**[0112]** As Fig. 6 best shows from another perspective, the stepped-up barrier 128 extends into the RBC mass and creates a restricted passage 129 between it and the facing high-G wall 66. The restricted passage 129 allows RBC present along the high-G wall 66 to move beyond the barrier 128 for collection by the RBC collection passage 126. Simultaneously, the stepped-up barrier 128 blocks the passage of the PRP beyond it, keeping the PRP within the dynamic flow conditions leading to the PRP collection region 124.

**[0113]** While various configurations can be used, in a preferred arrangement, the low-G wall 64 tapers about 2 mm into the chamber 74 where it joins the barrier 128. The barrier 128 extends from there at about a 45 degree angle toward the high-G wall 66, forming a raised planar surface. The passage 129 formed between the planar surface and the high-G wall 66 is about 1 mm to 2 mm

in radial depth and about 1 mm to 2 mm in circumferential length.

**[0114]** As previously described (and as Fig. 6 shows), the configuration of the low-G wall 64 creates a swift counterflow of plasma from the RBC collection region toward the PRP collection region 124.

**[0115]** The desired contours for the low-G wall 64 of the alternative chamber assemblies 74 and 76 can be preformed on the exterior surface of the spool element 82. In the illustrated embodiment, the interior surface of the bowl element 82 is isoradial with respect to the rotational axis.

**[0116]** Also in both alternative embodiments (as Figs. 9 and 11 show), the dog leg portion 120 of the RBC collection passage 126 is tapered. Due to the taper, the passage 126 presents a greater cross section where it opens into the chamber 84 than it does where it joins the axial first region 118 of the RBC collection passage 126. Fig. 6 shows this taper from another perspective. In the illustrated and preferred embodiment, the dog leg portion 120 tapers from a width of about 6.35 to 3.18mm (1/4 inch to 1/8 inch)

**[0117]** The taper of the dog leg portion 120 is preferably gauged relative to the taper of the low-G wall 64 to keep the cross sectional area of the RBC collection passage 126 substantially constant. This keeps fluid resistance within the passage 126 relatively constant, while maximizing the available separation and collection areas outside the passage 126. The taper of the dog leg portion 120 also facilitates the removal of air from the passage 126 during priming.

**[0118]** As Figs. 9 and 11 best show, a ramp 130 extends from the high-G wall 66 across the PRP collection region 124 in each alternative chamber assembly 74 and 76. As Fig. 17 shows from another perspective, the ramp 130 forms a tapered wedge that restricts the flow of fluid toward the PRP collection port 72. As Fig. 18 shows, the ramp 130 forms a constricted passage 131 along the low-G wall 64, along which the PRP layer extends.

**[0119]** In the illustrated embodiment (see Fig. 15), a hinged flap 132 extends from and overhangs a portion of the spool element 82. The flap 132 is preformed to present the desired contour of the ramp 130.

**[0120]** When flipped down (as Fig. 15 shows in solid lines), the flap 132 is sandwiched between the chosen chamber assembly 74/76 and the surrounding bowl element 80. The flap 132 presses against the adjacent flexible wall of the chamber assembly 74/76, which conforms to its contour to form the ramp 130 within the chamber 84.

**[0121]** As shown diagrammatically in Figs. 18A to C, the ramp 130 diverts the fluid flow along the high-G wall 66. This flow diversion changes the orientation of the interface 26 between the RBC (shown shaded in Figs. 18A/B/C) and the PRP (shown clear in Figs. 18A/B/C) within the PRP collection region 124. The ramp 130 displays the interface 26 for viewing through a side wall of

the chamber assembly 74/76 by an associated interface controller 134 (that Figs. 23 and 24 show).

[0122] As will be described in greater detail later, the interface controller 134 monitors the location of the interface 26 on the ramp 130. As Figs. 18A/B/C show, the position of the interface 26 upon the ramp 130 can be altered by controlling the relative flow rates of WB, the RBC, and the PRP through their respective ports 68/70/72. The controller 134 varies the rate at which PRP is drawn from the chamber 84 to keep the interface 26 at a prescribed location on the ramp 26 (which Fig. 18B shows), away from the constricted passage 131 that leads to the PRP collection port 72.

[0123] The ramp 130 and associated interface controller 134 keep RBC, white blood cells, and lymphocytes present in the interface 26 from entering the PRP collection port 72. The collected PRP is thereby essentially free of the other cellular components present in the interface 26.

### **B. The Second Stage Processing Chamber**

[0124] In the embodiment of the chamber assembly shown in Figs. 9/10, the fourth port 98 constitutes a PPP collection port 136, and the fifth port 100 constitutes a PRP inlet port 138. In the embodiment shown in Figs. 11/12, the opposite is true: the fourth port 98 constitutes the PPP inlet port 138, and the fifth port 100 constitutes the PPP collection port 136.

[0125] In each chamber assembly 74/76, the umbilicus 102 connects the PRP collection port 72 of the first chamber 84 with the PRP inlet port 138 of the associated second chamber 86. The second chamber 86 thereby receives PRP from the first chamber 84 for further separation into PPP and PC. The umbilicus 102 conveys separated PPP from the second chamber 86 through the associated PPP collection port 136. In each assembly 74/76, the PC remains behind in the second chamber 86 for later resuspension and collection.

[0126] In the alternative embodiments shown in Figs. 9/10 and 11/12, a fifth interior seal 140 extends between the PRP inlet port 138 and the PPP collection port 136. The fifth seal 140 includes a first region 142 that is generally parallel to the second seal 90, thereby extending across the circumferential flow path. The fifth interior seal 140 then bends in a dog-leg portion 144 away from the PRP inlet port 138 in the direction of circumferential PRP flow within the second chamber 86. The dog-leg portion 144 terminates near the longitudinal side edge of the second chamber 86 that is opposite to the longitudinal side edge formed by the second interior seal 90.

[0127] In the Figs. 9/10 embodiment, the fifth interior seal 140, the second interior seal 90, and the lower regions of the first peripheral seal 88 together form a PPP collection passage 146 that extends first along the axis of rotation (i.e., between the second interior seal 90 and the fifth interior seal 140) and then bends in a circumferential path to open near the end of the intended PRP

circumferential flow path (i.e., between the dog-leg portion 144 of the fifth seal 140 and the lower region of the peripheral seal 88). The PPP collection passage 146 receives PPP at its open end and from there channels the PPP to the PPP collection port 136.

[0128] In the Figs. 11/12 embodiment, a similar PPP collection passage 146 is formed between the fifth interior seal 140 and the upper region of the peripheral seal 88.

[0129] In each alternative circumferential flow chamber assembly 74/76, PRP entering the second chamber 86 via the PRP inlet port 138 is caused to flow first in an axial path from the axially oriented PRP inlet port 138 alongside the axially extending fifth seal 140. The flow direction of the PRP then turns to a circumferential path away from the fifth seal 140 toward the opposite longitudinal side edge.

[0130] The centrifugal forces generated during rotation of the chamber separate the PRP into PC and PPP. The more dense PC separate out into a layer that extends along the high-G wall 66. The less dense PPP is displaced toward the low-G wall 64 for collection through the PPP collection passage 146.

[0131] The inventor has discovered that the introduction of PRP along an axial flow path parallel to the axis of rotation into a circumferential flow path about the axis of rotation creates a non-turbulent vortex region 148, called a Taylor column, at the outlet of the PRP inlet port 138, as Fig. 19 shows.

[0132] The vortex region 148 circulates about an axis that is aligned with the axis of the PRP inlet port 138. The vortex region 148 stretches from the outlet of the port 138 longitudinally across the circumferential flow path of the chamber 86. As Fig. 19 shows, the vortex region 148 circulates the PRP about its axis and directs it into the desired circumferential flow path within the chamber 86.

[0133] Within the vortex region 148, axial flow velocity decreases in a generally linear fashion across the circumferential flow path of the chamber 86. This occurs as the axial flow of fluid entering the chamber 86 perfuses uniformly into a circumferential flow entering the separation zone.

[0134] A similar vortex region 148 forms at the opposite longitudinal end of the second chamber 86 at the entrance to the PPP collection passage 146, as Fig. 19 also shows.

[0135] The vortex region 148 created at the outlet of the PRP inlet port 138 uniformly disperses PRP in the desired circumferential flow path into the centrifugal field. This maximizes the exposure of the entering PRP to the effects of the centrifugal field across the effective surface area of the second chamber 86. Maximum possible separation of PC from the entering PRP results.

[0136] It should be noted that similar vortex region 148 flow conditions are formed in the first chamber 84 as well, where fluid either enters or leaves the established circumferential flow path through an axial flow

path. As Fig. 19 shows, a vortex region 148 condition thereby forms at the entrance of the WB inlet passage 122. Another vortex region 148 condition forms at the opposite longitudinal end at the entrance of the RBC collection passage 126.

[0137] In both alternative chamber assemblies 74/76 (as Figs. 10 and 12 show), the low-G wall 64 tapers into the second chamber 86 in the direction of circumferential PRP flow. The taper proceeds from the second interior seal 90 toward the opposite longitudinal end of the second chamber 86.

[0138] Also in both alternative chamber assemblies 74/76 (as Figs. 9 and 11 show), the circumferential leg of the associated PPP collection passage 146 is tapered. Due to the taper, the leg presents a greater cross section where it opens into the second chamber than it does where it joins the axial portion of the PPP collection passage 146. In the illustrated and preferred embodiment, the leg tapers from a width of about 6.35 to 3.18mm (1/4 inch to 1/8 inch).

[0139] As with the taper of the dog leg portion 120, the taper of the circumferential leg of the PPP collection passage 146 is preferably gauged relative to the taper of the low-G wall 64 to keep the cross sectional area of the PPP collection passage 146 substantially constant. This keeps fluid resistance within the passage 146 relatively constant. The taper of the circumferential leg of PPP collection passage 146 also facilitates the removal of air from the passage 146 during priming.

[0140] The dimensions of the various regions created in the processing chamber can of course vary according to the processing objectives. Table 2 shows the various dimensions of a representative embodiment of a processing chamber of the type shown in Figs. 9/10 or 11/12. Dimensions A through F referenced in Table 2 are identified for their respective chamber assemblies in Figs. 9 and 11.

TABLE 2

Overall length (A):	19-1/2 inches
Overall height (B):	2-13/16 inches
First stage Processing Chamber	
Length (C):	10-1/8 inches
Width (D):	2-3/8 inches
Maximum Radial Depth in Use:	4 mm
Second Stage Processing Chamber	
Length (E):	8-13/16 inches
Width (F):	2-3/8 inches
Maximum Radial Depth in Use:	4 mm
Port Spacing	
(center line to center line):	3/8 inch
(1 inch = 25.4mm)	

### III. SYSTEMS USING THE ENHANCED YIELD CIRCUMFERENTIAL FLOW CHAMBER FOR PLATELET SEPARATION AND COLLECTION

[0141] The two stage circumferential flow chambers shown in either Figs. 9/10 or Figs. 11/12 can be used to do continuous platelet collection. The chambers can be used in association either with a system 150 that employs one phlebotomy needle (as Fig. 20 shows) or with a system 152 that employs two phlebotomy needles (as Fig. 21 shows). In each system 150 and 152, an associated processing controller 154 automates the collection procedure to the fullest extent possible.

#### A. Single Needle Enhanced Yield Platelet Collection System

[0142] The platelet collection system 150 shown in Fig. 20 employs one, single lumen phlebotomy needle 156. Fig. 14 generally depicts this single needle system 150 when mounted for use on the centrifuge 78.

[0143] The processing controller 154 operates the single needle system 150 in a draw cycle and a return cycle.

[0144] During the draw cycle, the controller 154 supplies the donor's WB through the needle 156 to a chosen one of the processing chamber assemblies 74/76. There, the WB is centrifugally separated into RBC, PC, and PPP.

[0145] During the return cycle, the controller 154 returns RBC and PPP to the donor through the needle 156, while separation within the chosen processing chamber assembly 74/76 continues without interruption. The harvested PC is retained for long term storage. If desired, all or some PPP can be retained for storage, too.

[0146] The system 150 includes a draw reservoir 158, which pools a quantity of the donor's WB during the draw cycle. The system 150 also includes a return reservoir 160, where a quantity of RBC collect for periodic return to the donor during the return cycle.

[0147] Processing containers associated with the system 150 include a container 162 that holds anticoagulant for use during the procedure and a container 164 that holds saline solution for use in priming and purging air from the system 150 before the procedure. The system further includes collection containers 166 for receiving PC (and optionally PPP) for storage.

[0148] When the controller 154 operates the system 150 in the draw cycle, a first branch 168 directs WB from needle 156 to the draw reservoir 158, in association with the draw pumping station 170 and a clamp 172. An auxiliary branch 174 delivers anticoagulant to the WB flow in association with an anticoagulant pumping station 176.

[0149] A second branch 178 conveys the WB from the draw reservoir 158 to the WB inlet port 68 of the chosen processing chamber assembly 74/76, in association

with the WB inlet pumping station 180. The draw pumping station 170 operates at a higher flow rate (at, for example, 100 ml/min) than the WB inlet pumping station 180, which operates continuously (at, for example, 50 ml/min).

[0150] The processing controller 154 includes a first scale 182 that monitors the weight volume of WB collected in the draw reservoir 158. The first scale 182 intermittently operates the draw pumping station 170 to maintain a desired weight volume of WB in the draw reservoir 158.

[0151] Once the desired volume of WB is present in the draw reservoir 158, the WB inlet pumping station 180 operates to continuously convey WB into the chosen processing chamber assembly 74/76.

[0152] The draw pumping station 170 continues to operate periodically during the draw cycle in response to the scale 182 to maintain the desired weight volume of WB in the draw reservoir 158.

[0153] The WB enters the first stage chamber 84, where it is separated into RBC and PRP. This separation process has already been described.

[0154] A third branch 184, in association with the plasma pumping station 186, draws the PRP from the PRP collection port of the first processing chamber 84. The third branch 184 conveys the PRP to the PRP inlet port 138 of the second processing chamber 86. There, the PRP is further separated into PC and PPP. This separation process has already been described.

[0155] As will be described in greater detail later, the processing controller 154 monitors the location of the interface on the ramp 130 via the interface controller 134. The controller 154 operates the plasma pumping station 186 to keep the maximum rate of the variable plasma pumping station 186 (for example, 25 ml/min) less than the WB inlet pumping station 180.

[0156] A fourth branch 188 conveys the RBC from the RBC collection port 74 of the first stage processing chamber 84. The fourth branch 188 leads to the return reservoir 160.

[0157] The processing controller 154 includes a second scale 190 that monitors the weight volume of RBC in the return reservoir 160. When a preselected weight volume exists, the controller 154 shifts the operation of the system 150 from its draw cycle to its return cycle.

[0158] In the return cycle, the controller 154 stops the draw pumping station 170 and starts a return pumping station 192. A fifth branch 194 associated with the return pumping station 192 conveys RBC from the return reservoir 160 to the needle 156.

[0159] Meanwhile, while in the return cycle, the controller 154 keeps the WB inlet pumping station 180 and plasma pumping station 186 in operation to continuously process the WB pooled in the draw reservoir 158 through the first processing chamber 84.

[0160] During both draw and return cycles, PRP enters the PRP inlet port 138 of the second stage processing chamber 86. The PPP exits the PPP collection port

136 of the second stage processing chamber through a sixth branch 196 and into the return reservoir 160, joining the RBC there pooled.

[0161] Alternatively, by closing the clamp 198A and opening the clamp 198B, the PPP can be conveyed through a seventh branch 200 to one or more collection containers 166.

[0162] After a procedure, the PC collected within the second processing compartment 86 is transferred via the seventh branch 200 to one or more collection containers 166 for storage.

## B. Double Needle Platelet Collection System

[0163] The platelet collection system 152 shown in Fig. 21 employs two single lumen phlebotomy needles 202A and 202B to obtain generally the same processing results as the single needle system 150 shown in Fig. 20. Elements common to both systems 150 and 152 are assigned the same reference numeral.

[0164] The associated processing controller 154 operates the system 152 in a continuous cycle, during which the donor's WB is continuously supplied through the needle 202A to the chosen processing chamber assembly 74/76 for separation into RBC, PC, and PPP, while RBC and PPP are continuously returned to the donor through the needle 202B.

[0165] As in the single needle system 150, the harvested PC is retained for long term storage. If desired, all or some PPP can be diverted from the donor for storage.

[0166] As in the single needle system 150, the processing containers associated with the double needle system 152 include a container 162 that holds anticoagulant and a container 164 that holds saline solution for use in priming and purging air from the system 152.

[0167] The system 152 also includes similar collection containers 166 for receiving PC (and optionally PPP) for storage.

[0168] Under the control of the controller 154, a first branch 204 directs WB from the needle 202A to the WB inlet port 68 of the first stage processing chamber 84, in association with the WB inlet pumping station 206, which operates continuously at, for example, 50 ml/min. An auxiliary branch 174 delivers anticoagulant to the WB flow in association with an anticoagulant pumping station 176.

[0169] The WB enters and fills the first processing chamber 84 in the manner previously described, where centrifugal forces generated during rotation of the chosen chamber assembly 74/76 separate the WB into RBC and PRP.

[0170] A second branch 208, in association with the plasma pumping station 210, draws the PRP layer out the PRP collection port 72 of the first stage processing chamber 84, conveying the PRP to the PRP inlet port 138 of the second stage processing chamber 86, where it undergoes further separation into PC and PPP.

[0171] The processing controller 154 monitors the location of the interface on the ramp 130 and varies the speed of the plasma pumping station 210 (using the interface controller 134, to be described later in greater detail) to keep the interface 26 at a prescribed location on the ramp 130. As before described, the controller 154 keeps the maximum rate of the variable plasma pumping station 210 (for example, 25 ml/min) less than the WB inlet pumping station 206.

[0172] A third branch 212 conveys the RBC from the RBC collection port 70 of the first stage processing chamber 84. The third branch 212 leads to the needle 202B.

[0173] The PPP exits the PPP collection port 136 of the second stage processing chamber 86 through a fourth branch 214, joining the third branch 212 (carrying RBC) leading to the needle 202B. Alternatively, by closing the clamp 216A and opening the clamp 216B, the PPP can be conveyed through a fifth branch 218 to one or more collection containers 166.

[0174] After a procedure, the PC collected within the second processing compartment 86 is transferred via the fifth branch 218 to one or more collection containers 166 for storage.

### **C. Enhancing Platelet Separation by Plasma Recirculation**

[0175] Both single and double needle systems 150 and 152 (shown in Figs. 20 and 21 respectively) include a recirculation branch 220 and an associated recirculation pumping station 222. The processing controller 154 has a recirculation control system 224 that operates the pumping station 222 to convey a portion of the PRP exiting the PRP collection port 72 of the first processing compartment 84 for remixing with the WB entering the WB inlet port 68 of the first processing compartment 84.

[0176] The control system 224 can control the recirculation of PRP in different ways.

[0177] As Fig. 22 shows, the recirculation control system 224 includes a sensor 226 that senses the flow rate at which PRP exits the first processing compartment 84, under the control of pumping station 186 (for the single needle system 150) or pumping station 210 (for the double needle system 152). As will be described in greater detail, this flow rate is itself controlled by the interface controller 134.

[0178] The recirculation control system 224 employs a comparator 228 to compare the sensed PRP flow rate to an established desired flow rate. If the sensed rate is less than the desired flow rate, the comparator 228 sends a signal to increase the rate at which the recirculation pumping station 222 operates. And, if the sensed rate is more than the desired flow rate, the comparator 228 sends a signal to decrease the rate at which the recirculation pumping station 222 operates. In this way, the comparator 228 maintains the PRP flow rate at the desired rate.

[0179] The desired PRP output rate is preselected to create within the first compartment 84 the processing conditions which maximize the concentration of platelets in the PRP stream.

[0180] The desired rate of recirculation is based upon the radial flow rate of plasma desired in the region where PRP is collected.

[0181] The pumping rate of the recirculation pump 222 is maintained as a percentage (%<sub>RE</sub>) of the pumping rate of the whole blood inlet pump 180/206, governed as follows:

$$\%_{RE} = K * Hct - 100$$

where:

Hct is the hematocrit of the donor's whole blood, measured before donation, and

K is a dilution factor that takes into account the volume of anticoagulant and other dilution fluids (like saline) that are added to the donor's whole blood before separation.

[0182] According to this aspect the pumping rate of the recirculation pump 222 is maintained at the predetermined percentage (%<sub>RE</sub>) of the pumping rate of the whole blood inlet pump 180/206 to maintain a surface hematocrit of about 30% to 35% in the entry region R<sub>c</sub>. The preferred surface hematocrit in the entry region R<sub>c</sub> is believed to be about 32%.

[0183] Keeping the surface hematocrit in the entry region R<sub>c</sub> in the desired range provides optimal separation of RBC from PRP, thereby optimizing the radial flow of plasma in this region. If the surface hematocrit exceeds the predetermined range, radial plasma flow in the entry region R<sub>c</sub> decreases. If the surface hematocrit falls below the predetermined range, the radial flow of PRP increases enough to sweep small RBC's and white blood cells into the PRP.

[0184] The value of the dilution factor K can vary according to operating conditions. The inventor has determined that K = 2.8, when ACD anticoagulant is added to constitute about 9% of the entry whole blood volume, and a saline dilution fluid is added in an amount representing about 4% of donor body volume (i.e., 200 ml saline for 5000 ml in body volume).

[0185] In an alternate arrangement (shown in phantom lines in Fig. 22), the recirculation control system 224 recirculates PPP, instead of PRP, based upon %<sub>RE</sub>, as determined above.

[0186] In this arrangement, the system 224 uses a recirculation branch 230 and associated pumping station 232 located downstream of the second processing compartment 86. The comparator controls the pumping station 232 in one of the same manners just described to mix PPP exiting the second compartment 86 with the incoming WB entering the first compartment 84.

**[0187]** By mixing PRP (or PPP) with the WB entering the first processing compartment 84 to control surface hematocrit in the entry region  $R_c$ , the velocity at which red blood cells settle toward the high-G wall 66 in response to centrifugal force increases. This, in turn, increases the radial velocity at which plasma is displaced through the interface 26 toward the low-G wall 64. The increased plasma velocities through the interface 26 elute platelets from the interface 26. As a result, fewer platelets settle on the interface 26.

#### Example 1

**[0188]** A study evaluated a two stage separation chamber 74 like that shown in Fig 9 in a platelet collection procedure on a healthy human donor. The chamber 74 was part of a double needle system 152, like that shown in 21. The system 152 recirculated PRP in the manner shown in Fig. 21 to obtain a hematocrit of 32.1% in the PRP collection region 124 of the chamber 74.

**[0189]** In this study, the low-G wall 64 of the first stage chamber 84 was not tapered in the direction of circumferential flow from the PRP collection region 124. The low-G wall 64 was isoradial along the circumferential flow path in the first stage chamber 84, except for the presence of a RBC barrier 128, which stepped into the chamber across the RBC collection passage, as shown in Fig. 10. The low-G wall 64 was isoradial along the entire circumferential flow path of the second chamber 86.

**[0190]** Fig. 28A shows the platelet count sampled in the PRP (in 1000 platelets per  $\mu\text{L}$ ) over time during the 45 minute procedure. As there shown, after a run time of 6 minutes, the platelet count was 173; after 10 minutes, the platelet count was 304; and after 20 minutes, the platelet count stabilized at 363.

**[0191]** Fig. 28B shows the physical size of the platelets collected in the PRP in terms of mean platelet volume (in femtoliters) sampled during the procedure. As there shown, after a run time of 6 minutes, the mean platelet size was 6.6; after 20 minutes, the mean platelet size rose to 7.5; and at the end of the procedure, the mean platelet size was 8.2. A size distribution study of the PC collected showed that about 3% of the platelets collected were larger than 30 femtoliters (i.e., were very large platelets).

**[0192]** The platelet transfer efficiency in the first stage chamber 84 (i.e., the percentage of available platelets entering the first stage chamber 84 that were ultimately collected in the PRP) was 93.8%. In other words, the first stage chamber 84 failed to collect only 6.2% of the available platelets in the first stage chamber 84.

**[0193]** The platelet transfer efficiency in the second stage chamber 86 (i.e., the percentage of available platelets in the PRP entering the second stage chamber 86 that were ultimately collected as PC) was 99%. In other words, the second stage chamber 86 failed to collect only 1% of the platelets present in the PRP in the

second stage chamber 86.

**[0194]** The overall platelet collection efficiency of the chamber was about 81%, meaning that about 81% of the platelets in the whole blood processed were ultimately collected. This is a significantly higher amount than conventional processing can provide. In comparison, the comparable overall platelet collection efficiency for two stage CS-3000® Centrifuge chamber is about 50%.

**[0195]** This study demonstrates the increased separation efficiencies that result from chambers and systems that embody features of the invention.

#### Example 2

**[0196]** Another study evaluated a two stage separation chamber like that in Example 1 in a platelet collection procedure on a healthy human donor. As in Example 1, a double needle system was used. The system recirculated PRP to obtain an inlet hematocrit of 34.3%.

**[0197]** In this study, the low-G wall 64 of the first stage chamber 84 was tapered in the direction of circumferential flow from the PRP collection region 124, like that shown in Fig. 10. The low-G wall 64 also included RBC barrier 128 like that shown in Fig. 10. The low-G wall 64 was also tapered along the entire circumferential flow path of the second chamber 86.

**[0198]** Fig. 29A shows the platelet count sampled in the PRP (in 1000 platelets per  $\mu\text{L}$ ) over time during the 45 minute procedure. As there shown, a platelet count of 300 was achieved in the first 5 minutes of the procedure. The platelet count peaked at 331 after 21 minutes. At the end of the procedure, the platelet count was 302.

**[0199]** Fig. 29B shows the physical size of the platelets collected in the PRP in terms of mean platelet volume (in femtoliters) sampled during the procedure. As there shown, after a run time of only 5 minutes, the mean platelet size was 8.6, where it virtually remained throughout the rest of the procedure. A size distribution study of the PC collected showed that about 8.5% of the platelets collected were larger than 30 femtoliters.

**[0200]** The second study also experienced greater collection efficiencies.

**[0201]** The platelet transfer efficiency in the first stage chamber 84 (i.e., the percentage of available platelets that were ultimately collected in the PRP) was 99.2%. In other words, the first stage chamber 84 failed to collect less than 1% of the available platelets.

**[0202]** The platelet transfer efficiency in the second stage chamber 86 (i.e., the percentage of available platelets in the PRP that were ultimately collected as PC) was 99.7%. In other words, the second stage chamber 86 collected nearly all the platelets present in the PRP.

**[0203]** The overall platelet collection efficiency of the chamber was 85.3%.

**[0204]** This study further demonstrates the enhanced separation efficiencies that the invention can provide.

[0205] This study also shows the effect that the tapered low-G wall has in freeing greater number of platelets into the PRP stream. The effect is virtually immediate. After only 5 minutes in the second study, the platelet count was comparable to that encountered after 10 minutes in the first study.

[0206] This study also demonstrates the effect that the tapered low-G wall has in freeing larger platelets into the PRP stream. The effect, too, is virtually immediate. After the first 5 minutes of the procedure, the mean platelet size was comparable to that encountered after 30 minutes in the second study, which means that the larger platelets were already being collected. There were nearly 3 times more platelets of very large physical size (i.e., over 30 femtoliters) collected in the second study than in the first study.

#### **IV. INTERFACE CONTROL SYSTEMS FOR THE ENHANCED YIELD CIRCUMFERENTIAL FLOW CHAMBERS**

[0207] Figs. 23 to 27 show the details of an alternative interface control system 234, which can be used in association with either the single or double needle systems 150 or 152 previously described.

[0208] The interface control system 234 mounts the element that actually views the interface on a rotating element of the centrifuge. The system 234 relies upon a time pulse signal to determine the location of the interface.

[0209] As Figs. 23 and 24 A/B show, the interface control system 234 includes a light source 236 mounted on the yoke 85 of the centrifuge 78. The source 236 emits light that is absorbed by RBC. The control system 234 also includes a light detector 244 mounted next to the light source 236 on the yoke 85.

[0210] As Fig. 23 shows, a viewing head 238 carries both the light source 236 and the light detector 244 for rotation on the yoke 85. As previously described, the yoke 85 rotates at a one omega speed, carrying the viewing head 238 with it. At the same time, the spool and bowl assemblies 80 and 82 carried by the yoke 85 rotate at a two omega speed.

[0211] In the illustrated arrangement, the viewing head 238 also serves as a counterweight for the umbilicus holder 106 that the yoke 85 also carries (also see Figs. 13 and 14).

[0212] In the illustrated arrangement, the light source 236 includes a red light emitting diode. Of course, other colors, like green, could be used. In this arrangement, the light detector 244 comprises a PIN diode detector.

[0213] An optical pathway 240 directs light from the source diode 236 out onto the rotating bowl assembly 80 (see Fig. 24B). In the illustrated arrangement, the bowl assembly 80 is transparent to the light emitted by the source diode 236 only in the region where the bowl assembly 80 overlies the interface ramp 130.

[0214] The remainder of the bowl assembly 80 that

lies in the path of the viewing head 238 carries a light reflecting material 243. This differentiates the reflective properties of the interface region of the bowl assembly 80 from those of the remainder of the bowl assembly 80.

The material 243 could be light absorbing and serve the same purpose.

[0215] Alternatively, the source diode 236 could be gated on and off with the arrival and passage of the interface region of the bowl assembly 80 relative to its line of sight.

[0216] The interface ramp 130 carried by the spool assembly 82 is made of a light transmissive material. The light from the source diode 236 will thus pass through the transparent region of the bowl assembly 80 and the ramp 130 every time the rotating bowl assembly 80 and viewing head 238 align.

[0217] The spool assembly 82 also carries a light reflective material 242 on its exterior surface behind the interface ramp 130 (see Fig. 29). The material 242 reflects incoming light received from the source diode 236 out through the transparent region of the bowl assembly 80. The intensity of the reflected light represents the amount of light from the source diode 236 that is not absorbed by the RBC portion of the interface region.

[0218] The light detector 244 carried in the viewing head 238 receives the reflected light through an optical pathway. In the illustrated arrangement (see Fig. 24B), the optical pathway includes a lens 246, a penta prism 248, and an aperture 250.

[0219] In the illustrated arrangement, the lens 246 is about 9 mm in diameter, with the focal length of about 9 mm. In this arrangement, the lens 246 forms a real image with a magnification of about three. Alternatively, the real image could be made smaller to provide a better depth of field.

[0220] The aperture 250 is preferably small (about 0.75 mm in diameter) to allow only a small portion of the real image to reach the detector 244. The preferred viewing field of the detector 244 is therefore small, i.e., preferably on the order of about .25 mm in diameter.

[0221] The system 234 further includes a data link 278 for transmitting light intensity signals from the rotating viewing head 268 to an interface control circuit 270 on the stationary frame of the centrifuge. In the illustrated arrangement, the data link is optical in nature. Alternatively, slip rings could be used to transmit the light intensity signals as voltage or current signals.

[0222] The optical data link 278 includes a second light source 254. The second light source 254 is carried within the confines of a hollow light conduction passage 256 within the one omega drive shaft 257.

[0223] The optical data link 278 further includes a second light detector 268. The second detector 268 is carried on the non-rotating (i.e., zero omega) base of the centrifuge below the hollow one omega drive shaft 257. Light from the second light source 254 passes through the passage 256 and a collimating sleeve 259 to fall upon the second detector 268. Like the first detector 244, the



second detector 268 can comprise a PIN diode detector.  
**[0224]** The second light source 254 comprises at least one red light emitting diode carried within the passage 256 of the one omega shaft 257. Of course, other colors, like green, could be used.

**[0225]** In the illustrated arrangement (see Fig. 23), the second light source 254 includes three light emitting diodes 258 A/B/C arranged at 120 degree circumferentially spaced intervals within the passage 256. This arrangement minimizes interference due to misalignment between the second light source 254 and the second detector 268. In an alternative arrangement, the light intensity signal from the second detector 268 can be electronically filtered to eliminate interference signals caused by misalignment.

**[0226]** The optical data link 278 also includes an intensity control circuit 252 carried onboard the viewing head 238. The intensity control circuit 252 adjusts the input to the source diode 236 so that the intensity of light hitting the detector 244 remains constant.

**[0227]** The intensity control circuit 252 also connects the second light source 254 in series to the first mentioned light source 236. Thus, as the intensity control circuit 252 adjust the input to the first light source 236, it will also instantaneously adjust the input to the second light source 254. Thus the intensity of the light emitted by the source 254 is proportional to the intensity of light emitted by the source 236.

**[0228]** As Fig. 23 shows, the system 234 delivers electrical power to its rotating components through wires 251. The same wires 251 deliver power to the electric motor 253 that rotates the spool and bowl assemblies 80 and 82.

**[0229]** Fig. 25 shows a representative embodiment for the intensity control circuit 252. As shown, the control circuit 252 includes a transistor 260 that controls current flow to the series-connected first and second light sources 236 and 254.

**[0230]** The emitter of the transistor 260 is coupled to an amplifier 262. One amplifier input is coupled to the light detector 244 carried within the yoke viewing head 238. Another amplifier input is coupled to a reference diode 264. The circuit 252 also includes conventional current limiting resistors 266 to protect the light emitting diodes of the sources 236 and 254.

**[0231]** As the intensity of light hitting the detector 244 decreases, the output of the amplifier 262 increases. The transistor 260 conducts more current. The intensities of the first and second light sources 236 instantaneously increase by equal or otherwise proportional amounts.

**[0232]** Likewise, as the intensity of light hitting the detector 244 increases, the output of the amplifier 262 decreases. The transistor 260 conducts less current. The intensities of the first and second light sources 236 instantaneously decrease by equal or proportional amounts.

**[0233]** As Fig. 26A shows, the interface control circuit

270 converts the sensed light intensity output of the second detector 268 to amplified voltage signals. A conventional waveshaping circuit converts the amplified voltage signals to square wave time pulses.

**[0234]** From the time pulses, the interface control circuit 270 derives the physical dimension of the interface (measured in inches). The interface control circuit 270 then generates a pump control signal based upon any differences between the derived interface dimension and a desired interface dimension.

**[0235]** As Fig. 26A shows, the first detector 244 will view fully reflected light, free of diminution at a fixed intensity  $I_1$ , during the period the reflective bowl material 243 and the viewing head 238 are in alignment. The second detector 268 will also view light at a fixed intensity  $I_2$  generated by the second light source 254 during this period.

**[0236]** As the transparent interface region of the bowl assembly 80 comes into alignment with the viewing head 238, red blood cells displayed on the interface ramp 130 will enter the optical path of the viewing head 238.

**[0237]** The red blood cells absorb the light from the first light source 236. This absorption reduces the previously viewed intensity of the reflected light. With decreasing light intensity sensed, the control circuit 252 instantaneously increases the input to both first and second light sources 236 and 254 to maintain a constant light intensity at the first detector 244.

**[0238]** Under the control of the circuit 252, both light sources 236 and 254 will become brighter, assuming a new intensity level while the red blood cell band of the interface pass past the viewing head 238.

**[0239]** As Fig. 26B shows, the first detector 244 will not sense this relative increase in intensity over time, because the control circuit 252 instantaneously maintains the intensity  $I_1$  viewed by the first detector 244 constant. However, the second detector 268 will sense this relative increase in intensity  $I_2$  over time.

**[0240]** As Fig. 26B shows, the second detector 268 generates an increasing intensity output signal  $I_2$ . The interface control circuit 270 converts the increasing intensity signal into the leading edge 274 of the square pulse 272 shown in Fig. 26B. This event marks the beginning time ( $T_1$ ) of the pulse 272.

**[0241]** Eventually, the intensity signal will stabilize, as the most dense region of the red cell band of the interface enters the optical path of the viewing head 238. The interface control circuit 270 converts the stabilized intensity signal into the plateau 275 of the square pulse 272 shown in Fig. 26B.

**[0242]** When the red cell band of the interface leaves the optical path of the viewing head 238, the first detector 244 will again view fully reflected light from the reflective bowl material 243. With increasing light intensity sensed, the control circuit 252 will instantaneously decrease the input to both first and second light sources 236 and 254 to maintain a constant light intensity at the

first detector 244.

[0243] Again, the first detector 244 will not see this relative decrease in intensity over time, because the control circuit 252 instantaneously maintains the intensity  $I_1$  viewed by the first detector 244 constant. However, the second detector 268 will sense this relative decrease in intensity over time. The second detector 268 generates a decreasing intensity output signal  $I_2$ . The interface control circuit 270 converts this signal to the trailing edge 276 of the square pulse 272 shown in Fig. 26B. This event marks the ending time ( $T_2$ ) of the pulse 272.

[0244] As Figs. 26A and B show, the interface control circuit 270 measures, for each successive pulse 272A and 272B, the time period between the leading pulse edge 274 ( $T_1$  in Fig. 26) and the trailing pulse edge 276 ( $T_2$  in Fig. 26). This measurement ( $T_2$  minus  $T_1$ ) constitutes the length of the pulse (in seconds).

[0245] The interface control circuit 270 also preferably measures the time period between two successive pulses (shown as 272A and 272B in Fig. 26C). This period of time is measured between the leading edge 274 of the first pulse 272A ( $T_1$  in Fig. 26C) and the leading edge 274 of the next successive pulse 272B ( $T_3$  in Fig. 26C). This measurement constitutes the period of the adjacent pulses (in seconds).

[0246] After this measurement has been made, the interface control circuit 270 then resets  $T_3$  to  $T_1$  for the next pulse measurement cycle (see Fig. 27A).

[0247] As Fig. 27B shows, the interface control circuit 270 derives the physical dimensions of the red cell band of the interface from these time pulse measurements, based upon the following relationship:

$$\frac{P_L}{P_P} = \frac{D_I}{D_B}$$

where:

$P_L$  is the measured length of the pulse ( $T_2$  minus  $T_1$ ) (in seconds);

$P_P$  is the measured period of the pulse ( $T_3$  minus  $T_1$ ) (also in seconds);

$D_I$  is the length of the red cell band of the interface (in inches) to be derived; and

$D_B$  is the circumference of the bowl assembly 80 (in inches).

[0248] If the rate of rotation of the bowl assembly 80 remains constant during the period of pulse measurements, the reciprocal of the frequency of rotation in seconds ( $1/F_{rot}$ , in Hz) can be substituted for  $P_P$ .

[0249] Based upon the above relationship,  $D_I$  can be derived as follows:

$$D_I = \frac{P_L \times D_B}{P_P}$$

[0250] As Fig. 27B shows, the interface control circuit 270 compares the derived physical measurement of the interface  $D_I$  with a control value ( $D_C$ ) to generate an error signal (E).

[0251] The interface control value  $D_C$  can comprise a preselected fixed absolute value (in inches) that the user inputs. Alternatively, the interface control value  $D_C$  can be expressed as a percentage based upon the length of the interface ramp 130 (i.e., red cells should occupy no more than 30% of the interface ramp 130).

[0252] With reference now also to Fig. 18A, if the error signal (E) is positive, indicating that the red cell band of the interface is too large, the interface control circuit 270 generates a signal to reduce the pumping rate of the plasma pumping station 186/210 (see Fig. 27B). This pushes the RBC region away from the PRP collection port 72 back toward the desired control position (Fig. 18B), where the error signal (E) is zero.

[0253] With reference to Fig. 18C, if the error signal (E) is negative, indicating that the red cell band of the interface is too small, the interface control circuit 270 generates a signal to increase the pumping rate of the plasma pumping station 186/210 (see Fig. 27B). This pushes the RBC region toward the PRP collection port 72 back toward the desired control position (Fig. 18B), where the error signal (E) is again zero.

[0254] The optical data link 278 described above is representative of a broader class of systems for transmitting a control signal between a rotating element and a stationary element without mechanical contact between the two elements.

[0255] Like the illustrated optical data link 278, such a system employs sensor means on either the rotating or stationary element. The sensor means senses an operating condition that is subject to change. The sensor means generates a first output signal that varies according to changes in the sensed operating condition.

[0256] Like the illustrated optical data link 278, such a system includes an energy emitter on the one element that carries the sensor means. The emitter emits energy to the other element without mechanical contact with the other element. The emitter modulates the emitted energy according to variations occurring in the intensity of the first output signal. Alternatively, the sensor means itself can constitute an emitter of modulated energy.

[0257] The emitted energy used by the data link 278 is light. However, sound energy or other types of electromagnetic energy could be used as well.

[0258] Like the illustrated data link 278, the system includes a detector on the other element for receiving the modulated energy emitted by the emitter. The detector demodulates the detected energy to generate a second output signal that, like the first output signal, varies according to the changes in the sensed operating

condition.

[0259] Such a "connectionless" system for transmitting data between moving and stationary elements would be applicable for use for all sorts of real time control functions, not just interface control.

#### Claims

1. A method for centrifugally separating whole blood into red blood cells; plasma; and a platelet concentrate, the method comprising the steps of:

rotating a first compartment about a rotational axis, the compartment having radially spaced apart walls forming a separation zone with a high-G side and a low-G side located closer to the rotational axis than the high-G side, a blood flow path that extends circumferentially about the rotational axis, the said separation zone including an entry region (122) where whole blood enters the separation zone to begin separation and a terminal wall that is circumferentially spaced from the entry region, where separation is halted,

directing whole blood into the said separation zone (84) through a first path adjacent the entry region (122), to begin separation of the whole blood into red blood cells toward the high-G side and plasma constituent carrying platelets toward the low-G side,

directing red blood cells separated in the separation zone in a first circumferential flow direction toward the terminal wall,

halting blood flow in the first circumferential flow direction at the terminal wall,

successively increasing the surface hematocrit in the said separation zone in the first circumferential flow direction by separating the plasma constituent from the red blood cells,

directing separated red blood cells from the separation zone through a second path (126) adjacent the terminal wall, where the surface hematocrit in the separation zone is the most, directing plasma constituent separated in the separation zone in a second circumferential flow direction opposite to the first circumferential flow direction toward a different region (124) in the separation zone that is circumferentially spaced away from the terminal wall, said different region being next to the entry region but spaced therefrom, where the surface hematocrit in the separation zone is the least, and then

separating the plasma constituent into platelet concentrate and plasma in a second rotating compartment.

2. The method according to claim 1, further including circulating at least a portion of plasma separated in the second rotating compartment to the entry region (122) of the separation zone (84).

3. The method according to claim 1, further including circulating at least a portion of the plasma constituent separated in the separation zone (84) to the entry region (122) of the separation zone.

4. The method according to claim 1, further including introducing a fluid into the whole blood to lower the surface hematocrit of the blood in the separation zone (84).

5. A centrifugal separation apparatus for separating whole blood into red blood cells, plasma, and a platelet concentrate, the apparatus comprising

a first compartment having first and second walls spaced radially from the rotational axis and defining a first separation zone (84), the first separation zone forming a blood flow path extending circumferentially about the rotation axis that includes an entry region (122) where whole blood enters the first separation zone to begin separation and a terminal wall that is circumferentially spaced from the entry region, a first opening (68) in the first separation zone (84) adjacent the entry region (122) for directing whole blood into the first separation zone for separation into red blood cells and plasma constituent carrying platelets, means (116) for directing the red blood cells in a first circumferential flow direction toward the terminal wall, where blood flow in the first circumferential flow direction is halted, to successively increase the surface hematocrit in the first separation zone in the first circumferential flow direction,

a second opening in the first separation zone adjacent the terminal wall, where the surface hematocrit is the most, for directing red blood cells from the separation zone,

means (110) for directing the plasma constituent separated in the first separation zone in a second circumferential flow direction away from the terminal wall toward a different region (124) in the first separation zone that is circumferentially spaced away from the terminal wall and next to the entry region but spaced therefrom, and

a third opening (92) in the first separation zone (84) adjacent the different region (124) where the surface hematocrit is the least for directing plasma constituent separated in the first separation zone into a second separation compartment (86) defining a second separation zone

for separation into platelet concentrate and plasma.

6. The apparatus according to claim 5, further including a fourth opening in the second separation zone (86) to circulate at least a portion of plasma separated in the second separation zone to the entry region (122) of the first separation zone (84). 5
7. The apparatus according to claim 5, wherein the third opening (92) directs at least a portion of the plasma constituent separated in the first separation zone (84) to the entry region (122) of the first separation zone. 10
8. The apparatus according to claim 5, further including means communicating with the entry region (122) for introducing a fluid into the whole blood to lower the surface hematocrit of the blood in the first separation zone (84). 15 20

#### Patentansprüche

1. Verfahren zum Trennen von Vollblut durch Zentrifugieren in rote Blutzellen; Plasma; und ein Blutplättchenkonzentrat, wobei das Verfahren folgende Schritte aufweist: 25
  - Drehen eines ersten Abteils um eine Drehachse, wobei das Abteil radial beabstandete Wände aufweist, die eine Trennzone mit einer Seite mit hohem G-Wert und einer Seite mit niedrigem G-Wert bilden, die sich dichter an der Drehachse befindet als die Seite mit hohem G-Wert, ferner einen Blutströmungsweg aufweist, der sich in Umfangsrichtung um die Drehachse herum erstreckt, wobei die Trennzone einen Eintrittsbereich (122), in welchem das Vollblut in die Trennzone eintritt, um die Trennung zu beginnen, sowie eine Endwand aufweist, die in Umfangsrichtung von dem Eintrittsbereich beabstandet ist, wo die Trennung angehalten wird, 30
  - Zuführen von Vollblut in die Trennzone (84) durch eine erste Bahn, die an den Eintrittsbereich (122) angrenzt, um die Trennung des Vollblutes in rote Blutzellen zu der Seite mit hohem G-Wert hin und in einen Plasmabestandteil, der Blutplättchen aufweist, zu der Seite mit niedrigem G-Wert hin zu beginnen, 35
  - Zuführen der in der Trennzone abgetrennten roten Blutzellen in einer ersten Strömungsrichtung in Umfangsrichtung zu der Endwand hin, 40
  - Anhalten der Blutströmung in der ersten Strömungsrichtung in Umfangsrichtung an der Endwand, 45
  - Zunehmendes Erhöhen des Oberflächen-Hä-

matokritwertes in der Trennzone in der ersten Strömungsrichtung in Umfangsrichtung durch Trennen des Plasmabestandteils von den roten Blutzellen, /

- Zuführen der abgetrennten roten Blutzellen aus der Trennzone durch eine zweite Bahn (126), die an die Endwand angrenzt, wo der Oberflächen-Hämatokritwert in der Trennzone am höchsten ist,
- Zuführen des Plasmabestandteils, der in der Trennzone abgetrennt worden ist, in einer zweiten Strömungsrichtung in Umfangsrichtung, die der ersten Strömungsrichtung in Umfangsrichtung entgegengesetzt ist, zu einem anderen Bereich (124) in der Trennzone, der in Umfangsrichtung von der Endwand beabstandet ist, wobei der andere Bereich in der Nähe von dem Eintrittsbereich liegt, aber von diesem beabstandet ist, wo der Oberflächen-Hämatokritwert in der Trennzone am geringsten ist, und
- anschließendes Trennen des Plasmabestandteils in ein Blutplättchenkonzentrat und in Plasma in einem zweiten rotierenden Abteil.

2. Verfahren nach Anspruch 1, das ferner den Schritt aufweist, daß man zumindest einen Teil des Plasmas, der in dem zweiten rotierenden Abteil abgetrennt wird, zu dem Eintrittsbereich (122) der ersten Trennzone (84) zirkulieren läßt. 25
3. Verfahren nach Anspruch 1, das ferner den Schritt aufweist, daß man zumindest einen Teil des Plasmabestandteils, der in der Trennzone (84) abgetrennt wird, zu dem Eintrittsbereich (122) der Trennzone zirkulieren läßt. 30
4. Verfahren nach Anspruch 1, das ferner den Schritt aufweist, daß ein Fluid in das Vollblut eingeleitet wird, um den Oberflächen-Hämatokritwert des Blutes in der Trennzone (84) zu verringern. 35
5. Zentrifugaltrennvorrichtung zum Trennen von Vollblut in rote Blutzellen, Plasma und ein Blutplättchenkonzentrat, wobei die Vorrichtung folgendes aufweist: 40
  - ein erstes Abteil, das erste und zweite Wände aufweist, die in radialer Richtung von der Drehachse beabstandet sind und eine erste Trennzone (84) bilden, wobei die erste Trennzone eine Blutströmungsbahn bildet, die sich in Umfangsrichtung um die Drehachse herum erstreckt, wobei ein Eintrittsbereich (122) vorgesehen ist, in dem das Vollblut in die erste Trennzone eintritt, um die Trennung zu beginnen, und wobei eine Endwand vorgesehen ist, die in 45

- Umfangsrichtung von dem Eintrittsbereich beabstandet ist,
  - eine erste Öffnung (68) in der ersten Trennzone (84), die an den Eintrittsbereich (122) angrenzt, um das Vollblut in die erste Trennzone einzuführen, um die Trennung in rote Blutellen und einen Plasmabestandteil mit Blutplättchen vorzunehmen,
  - eine Einrichtung (116), um die roten Blutzellen in einer ersten Strömungsrichtung in Umfangsrichtung der Endwand zuzuführen, wo die Blutströmung in der ersten Strömungsrichtung in Umfangsrichtung angehalten wird, um sukzessive den Oberflächen-Hämatokritwert in der ersten Trennzone in der ersten Strömungsrichtung in Umfangsrichtung zu erhöhen,
  - eine zweite Öffnung in der ersten Trennzone, die an die Endwand angrenzt, wo der Oberflächen-Hämatokritwert am höchsten ist, um rote Blutzellen aus der Trennzone abzuführen,
  - eine Einrichtung (110), um den Plasmabestandteil, der in der ersten Trennzone abgetrennt wird, in eine zweite Strömungsrichtung in Umfangsrichtung weg von der Endwand einem anderen Bereich (124) in der ersten Trennzone zuzuführen, der in Umfangsrichtung von der Endwand beabstandet ist und dem Eintrittsbereich benachbart ist, aber von diesem beabstandet ist, und
  - eine dritte Öffnung (92) in der ersten Trennzone (84), die an den anderen Bereich (124) angrenzt, wo der Oberflächen-Hämatokritwert am geringsten ist, um den Plasmabestandteil, der in der ersten Trennzone abgetrennt wird, in ein zweites Trennabteil (86) einzuführen, das eine zweite Trennzone bildet, um eine Trennung in Blutplättchenkonzentrat und Plasma vorzunehmen.
6. Vorrichtung nach Anspruch 5, die ferner eine vierte Öffnung in der zweiten Trennzone (86) aufweist, um zumindest einen Teil des Plasmas, der in der zweiten Trennzone abgetrennt wird, zu dem Eintrittsbereich (122) der ersten Trennzone (84) zirkulieren zu lassen.
7. Vorrichtung nach Anspruch 5, wobei die dritte Öffnung (92) zumindest einen Teil des Plasmabestandteils, der in der ersten Trennzone (84) abgetrennt wird, dem Eintrittsbereich (122) der ersten Trennzone zuführt.
8. Vorrichtung nach Anspruch 5, die ferner eine Einrichtung aufweist, welche mit dem Eintrittsbereich (122) in Verbindung steht, um ein Fluid in das Vollblut einzuleiten, um den Oberflächen-Hämatokritwert des Blutes in der ersten Trennzone (84) zu verringern.

## Revendications

1. Procédé de séparation par centrifugation du sang entier en globules rouges, en plasma et en concentré de plaquettes, le procédé comprenant les étapes de:

mise en rotation d'un premier compartiment autour d'un axe de rotation, le compartiment comportant des parois espacées radialement formant une zone de séparation avec un côté à forte accélération et un côté à faible accélération situé plus près de l'axe de rotation que le côté à forte accélération, un trajet d'écoulement de sang qui s'étend de manière circonferentielle autour de l'axe de rotation, ladite zone de séparation comprenant une zone d'entrée (122) par laquelle le sang entier entre dans la zone de séparation afin de commencer la séparation, et une paroi extrême qui est espacée circonferentiellement par rapport à la zone d'entrée, sur laquelle la séparation est arrêtée, l'acheminement du sang entier dans ladite zone de séparation (84) à travers un premier trajet adjacent à la zone d'entrée (122) afin de commencer la séparation du sang entier en globules rouges vers le côté à forte accélération et en constituant de plasma supportant des plaquettes vers le côté à faible accélération, l'acheminement des globules rouges séparés dans la zone de séparation suivant une première direction d'écoulement circonferentielle vers la paroi extrême, l'arrêt de l'écoulement de sang suivant la première direction d'écoulement circonferentielle au niveau de la paroi extrême, l'augmentation successive de l'hématocrite de surface dans ladite zone de séparation suivant la première direction d'écoulement circonferentielle en séparant le constituant de plasma des globules rouges, l'acheminement des globules rouges séparés à partir de la zone de séparation à travers un second trajet (126) adjacent à la paroi extrême, sur laquelle l'hématocrite de surface dans la zone de séparation est le plus élevé, l'acheminement du constituant de plasma séparé dans la zone de séparation suivant une seconde direction d'écoulement circonferentielle opposée à la première direction d'écoulement circonferentielle vers une zone différente (124) dans la zone de séparation qui est espacée circonferentiellement par rapport à la paroi extrême, ladite zone différente étant proche de la zone d'entrée mais espacée de celle-ci, dans laquelle l'hématocrite de surface dans la zone de séparation est le plus faible, puis la séparation du constituant de plasma en con-

centré de plaquettes et plasma dans un second compartiment en rotation.

2. Procédé selon la revendication 1, comprenant, en outre, la mise en circulation d'au moins une partie de plasma séparée dans le second compartiment en rotation vers la zone d'entrée (122) de la zone de séparation (84). 5
3. Procédé selon la revendication 1, comprenant, en outre, la mise en circulation d'au moins une partie du constituant de plasma séparé dans la zone de séparation (84) vers la zone d'entrée (122) de la zone de séparation. 10
4. Procédé selon la revendication 1, comprenant, en outre, l'introduction d'un fluide dans le sang entier afin de réduire l'hématocrite de surface du sang dans la zone de séparation (84). 15
5. Dispositif de séparation par centrifugation destiné à séparer du sang entier en globules rouges, plasma et concentré de plaquettes, le dispositif comprenant: 20

un premier compartiment comportant des première et seconde parois espacées radialement par rapport à l'axe de rotation et définissant une première zone de séparation (84), la première zone de séparation formant un trajet d'écoulement de sang, s'étendant de manière circonférentielle autour de l'axe de rotation, qui comprend une zone d'entrée (122) dans laquelle du sang entier entre dans la première zone de séparation pour commencer la séparation et une paroi extrême qui est séparée circonférentiellement de la zone d'entrée, 30

une première ouverture (68) dans la première zone de séparation (84) adjacente à la zone d'entrée (122) afin d'acheminer le sang entier dans la première zone de séparation pour assurer la séparation en globules rouges et constituant de plasma supportant des plaquettes, 40

un moyen (116) destiné à acheminer les globules rouges dans une première direction d'écoulement circonférentielle vers la paroi d'extrémité, dans laquelle l'écoulement de sang dans la première direction d'écoulement circonférentielle est arrêté, pour augmenter successivement l'hématocrite de surface dans la première zone de séparation suivant la première direction d'écoulement circonférentielle, 50

une seconde ouverture dans la première zone de séparation adjacente à la paroi d'extrémité, dans laquelle l'hématocrite de surface est le plus important, afin d'acheminer les globules rouges à partir de la zone de séparation, 55

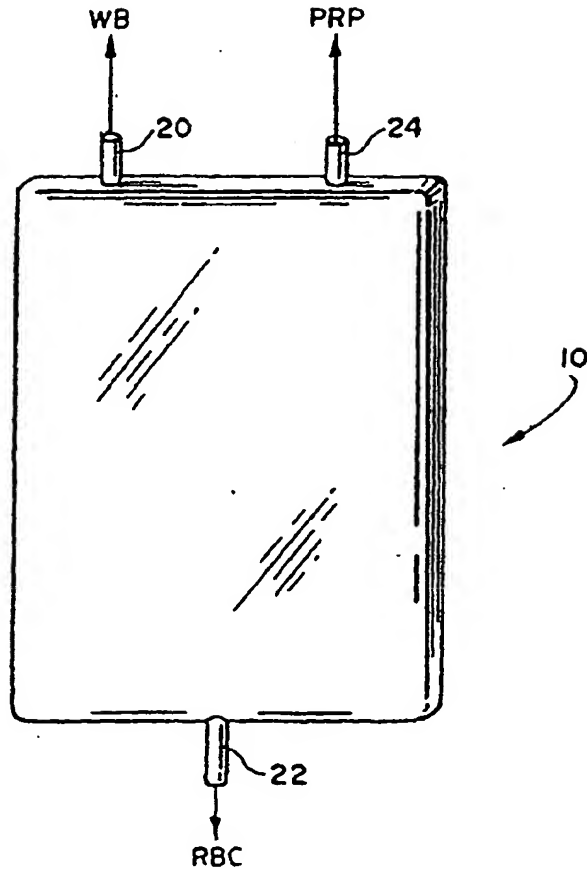
un moyen (110) destiné à acheminer le consti-

tuant de plasma séparé dans la première zone de séparation suivant une seconde direction d'écoulement circonférentielle s'écartant de la paroi d'extrémité vers une zone différente (124) dans la première zone de séparation qui est séparée circonférentiellement à l'écart de la paroi extrême et ensuite vers la zone d'entrée mais séparée de celle-ci, et

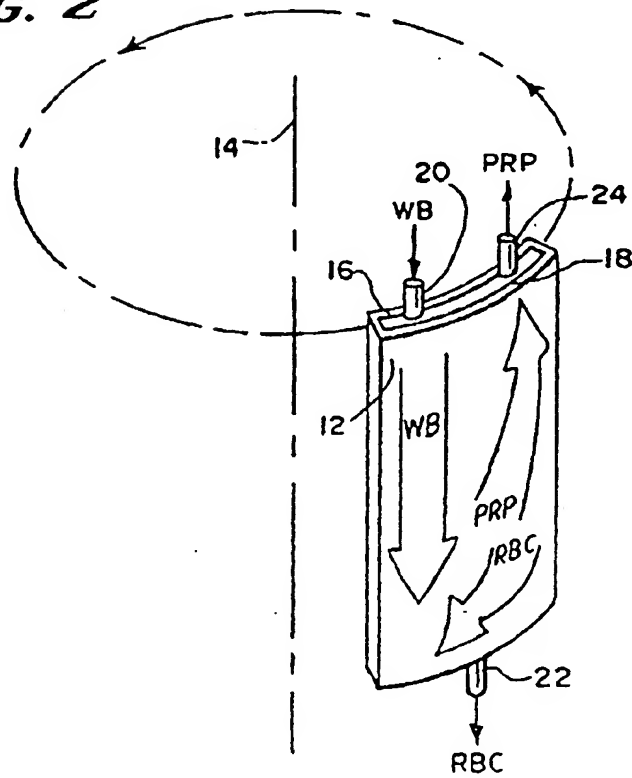
une troisième ouverture (92) dans la première zone de séparation (84) adjacente à la zone différente (124) dans laquelle l'hématocrite de surface est le plus faible afin d'acheminer un constituant de plasma séparé dans la première zone de séparation vers un second compartiment de séparation (86) définissant une seconde zone de séparation afin d'assurer la séparation en concentré de plaquettes et plasma.

6. Dispositif selon la revendication 5, comprenant, en outre, une quatrième ouverture dans la seconde zone de séparation (86) afin de faire circuler au moins une partie du plasma séparé dans la seconde zone de séparation vers la zone d'entrée (122) de la première zone de séparation (84). 25
7. Dispositif selon la revendication 5, dans lequel la troisième ouverture (92) achemine au moins une partie du constituant de plasma séparé dans la première zone de séparation (84) vers la zone d'entrée (122) de la première zone de séparation. 30
8. Dispositif selon la revendication 5, comprenant, en outre, un moyen communiquant avec la zone d'entrée (122) afin d'introduire un fluide dans le sang entier de manière à réduire l'hématocrite de surface du sang dans la première zone de séparation (84). 35

**FIG. 1**

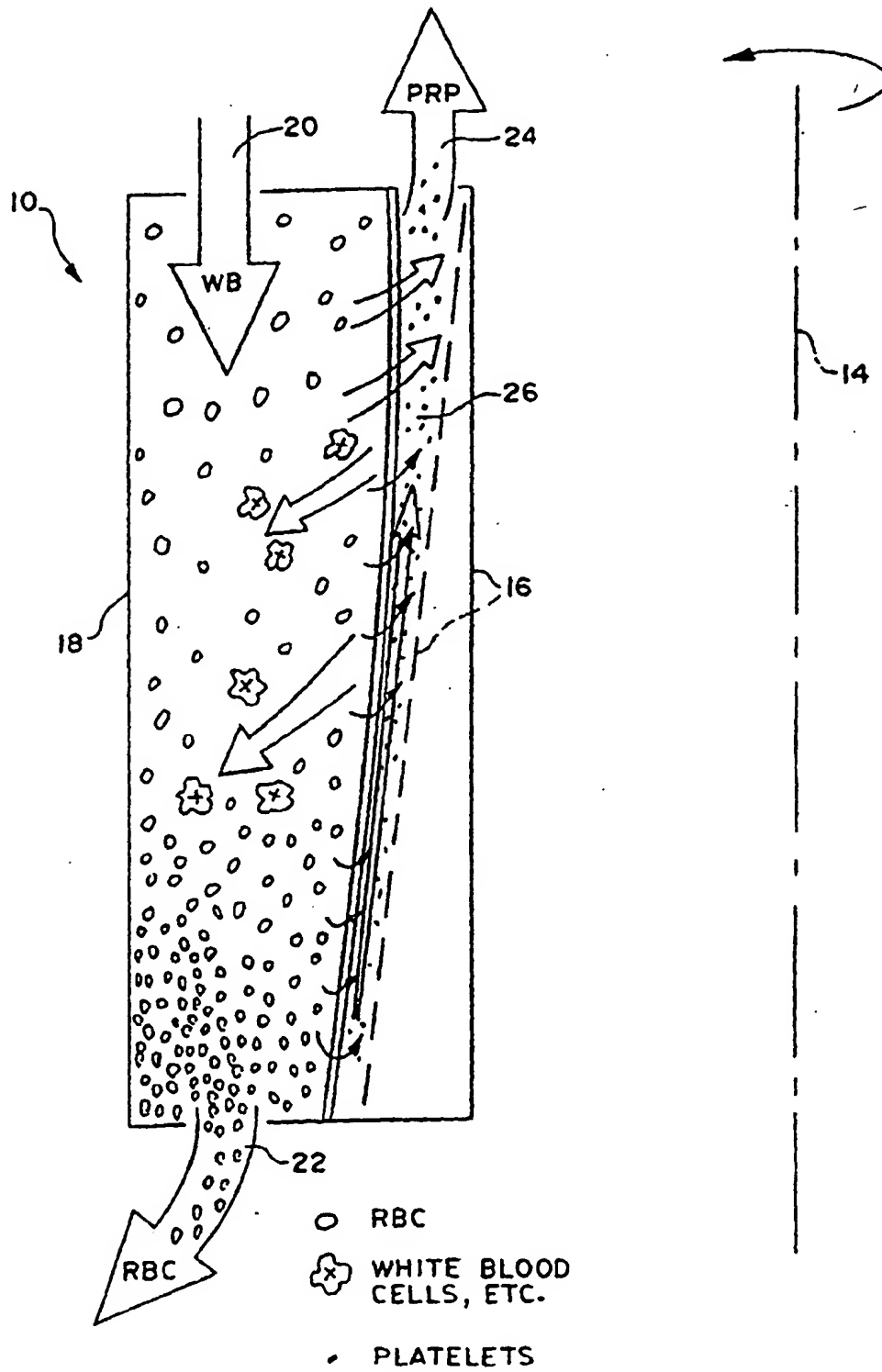


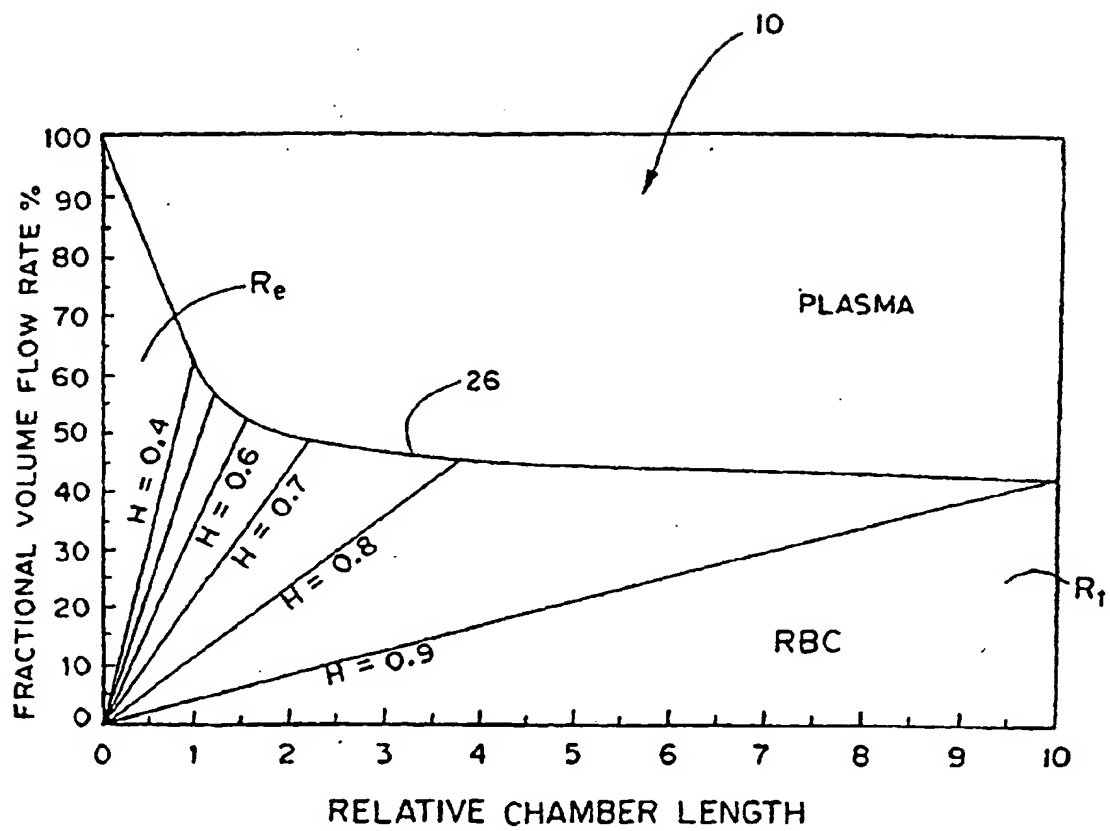
**FIG. 2**



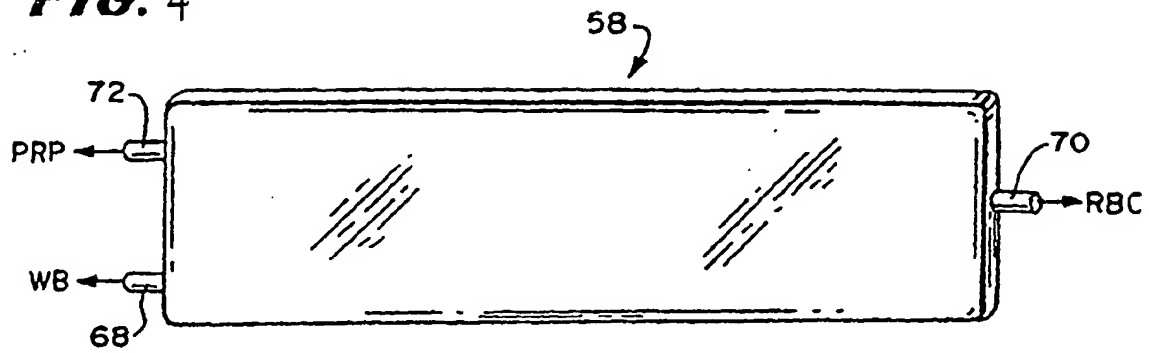


**FIG. 3**

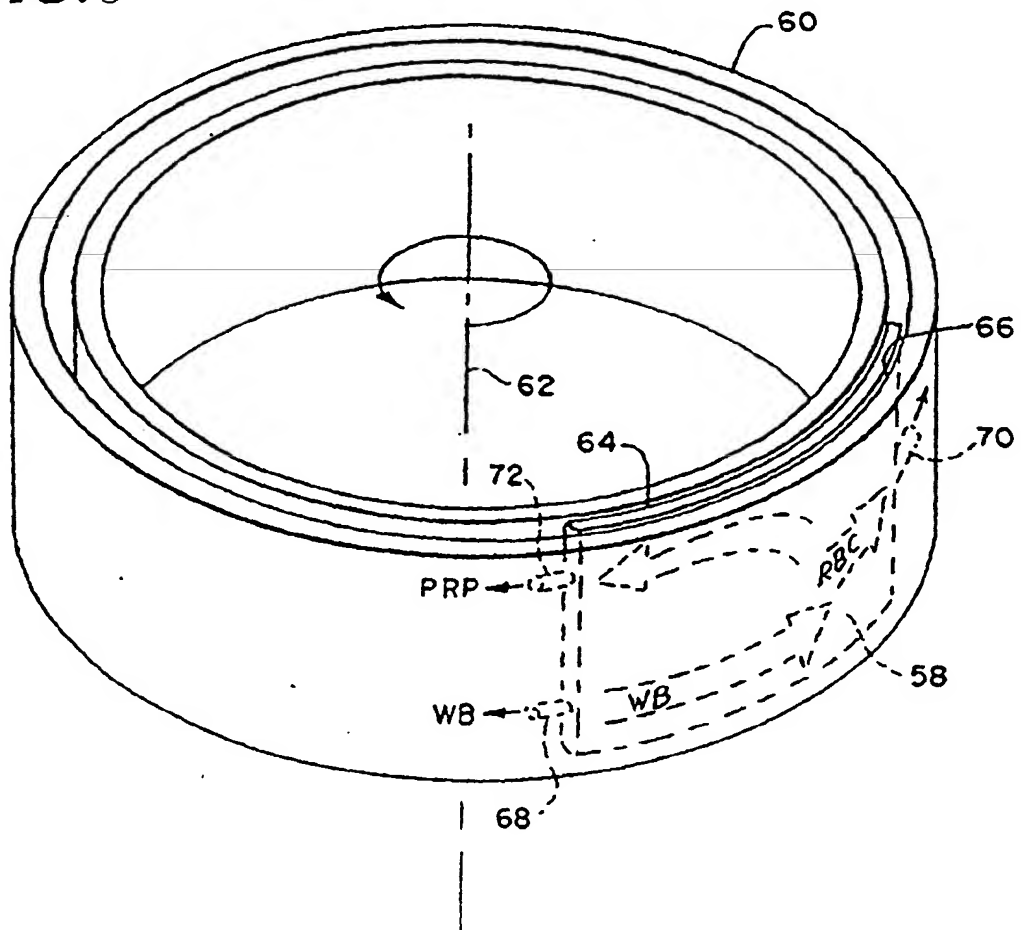


**FIG. 3A**

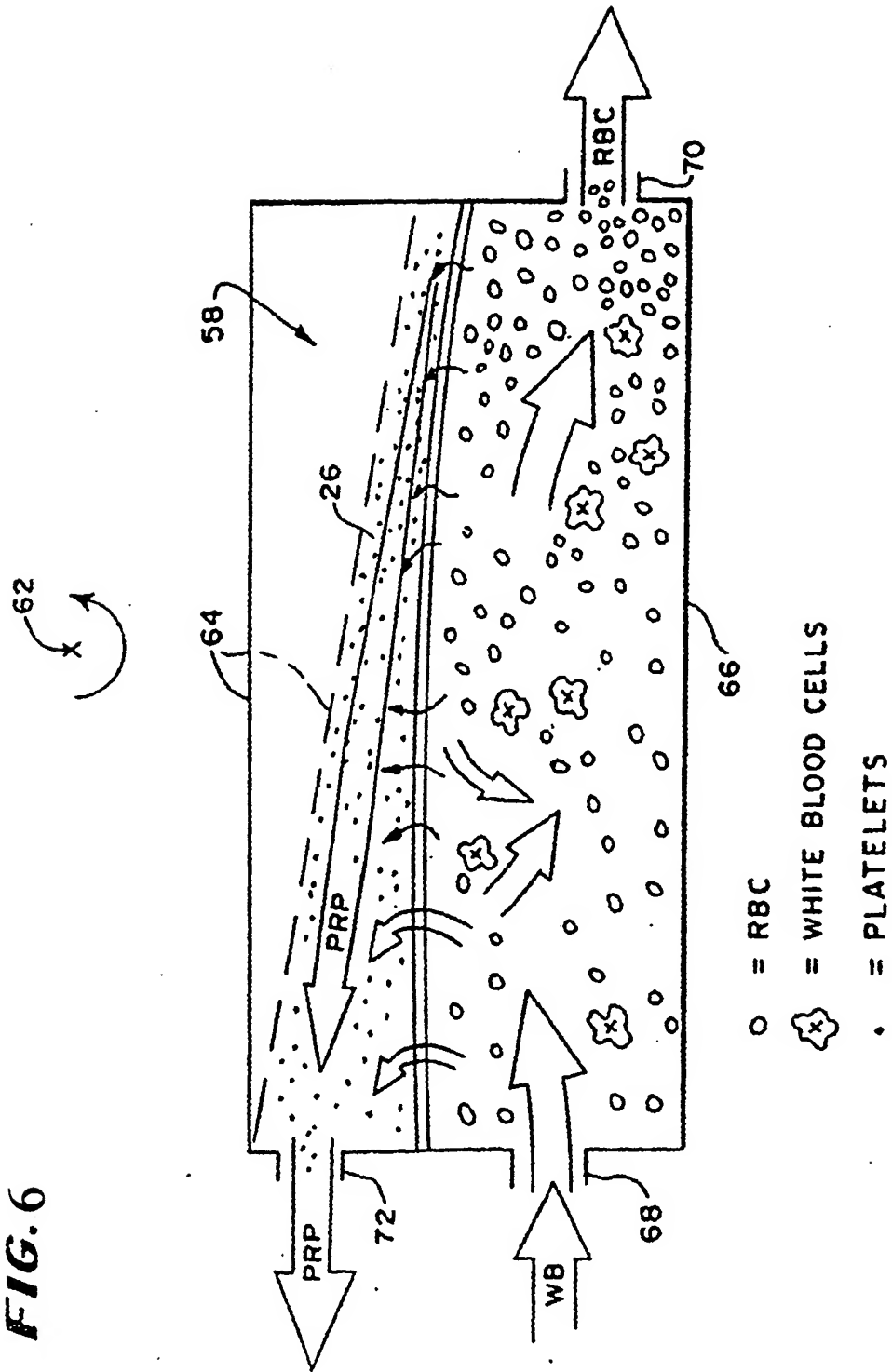
**FIG. 4**



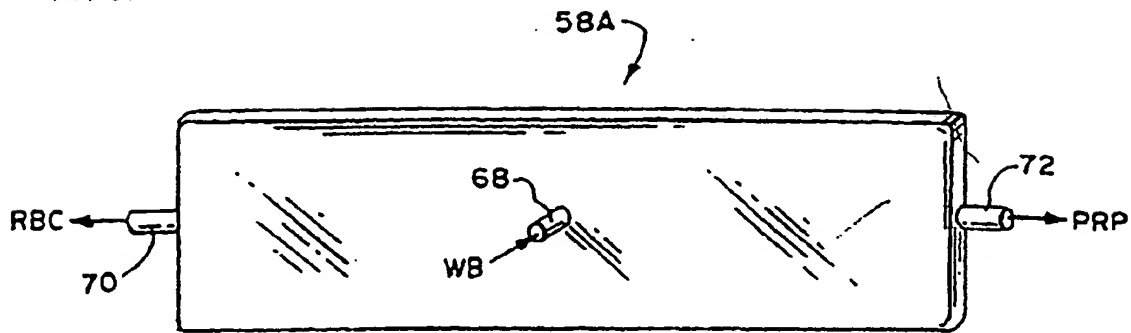
**FIG. 5**



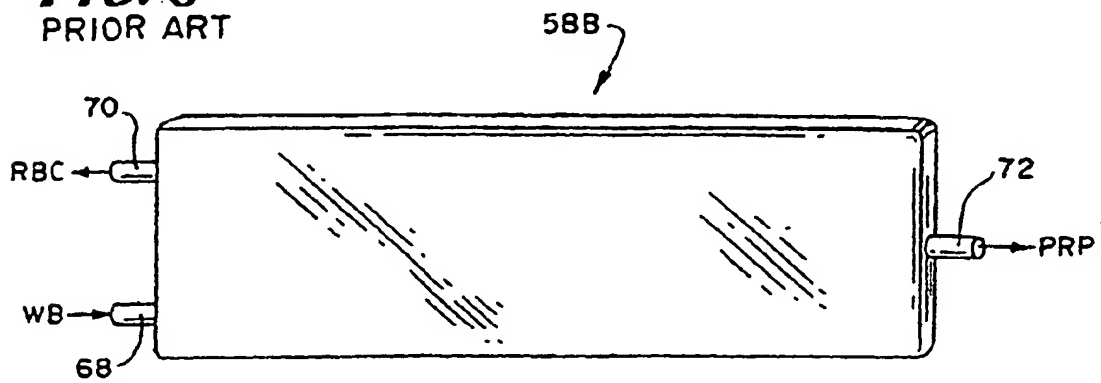
**FIG. 6**

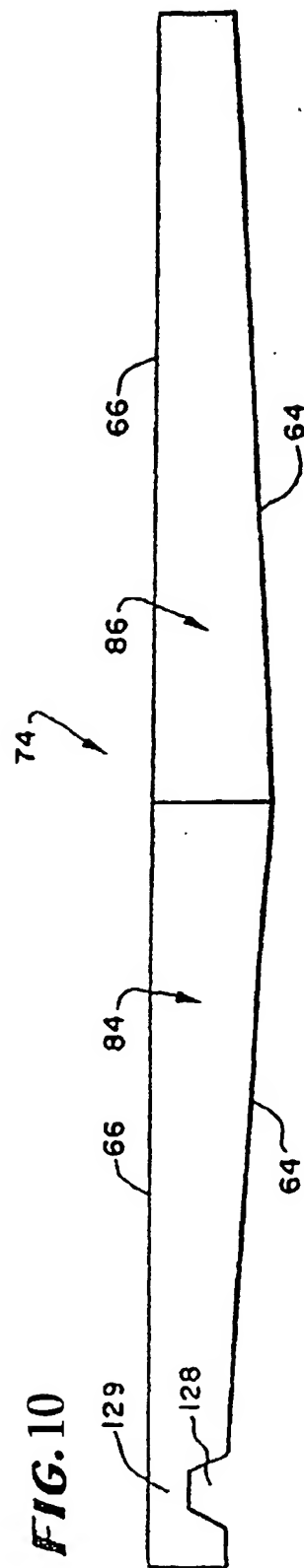
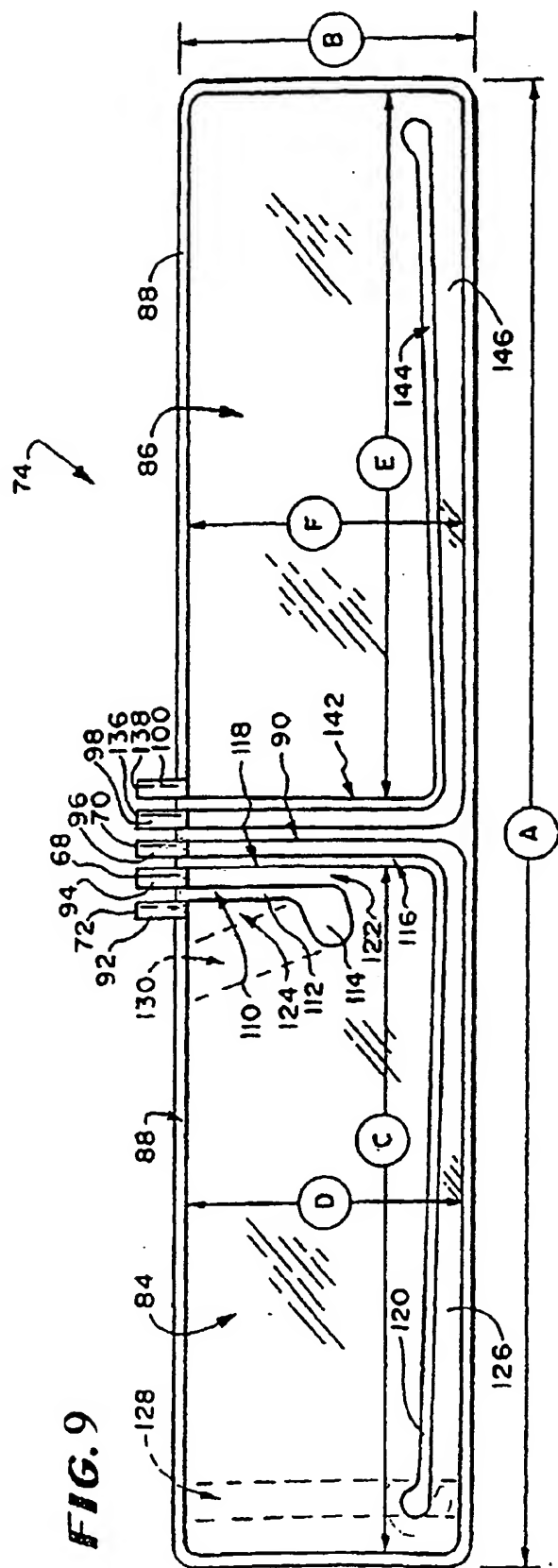


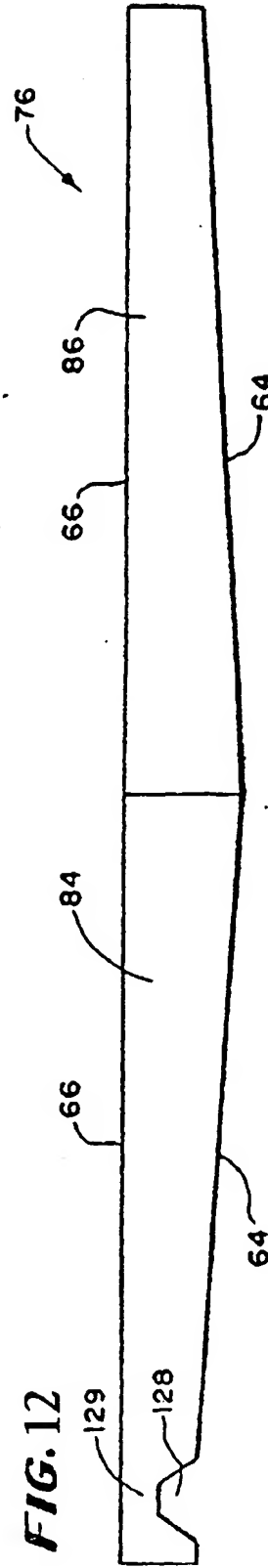
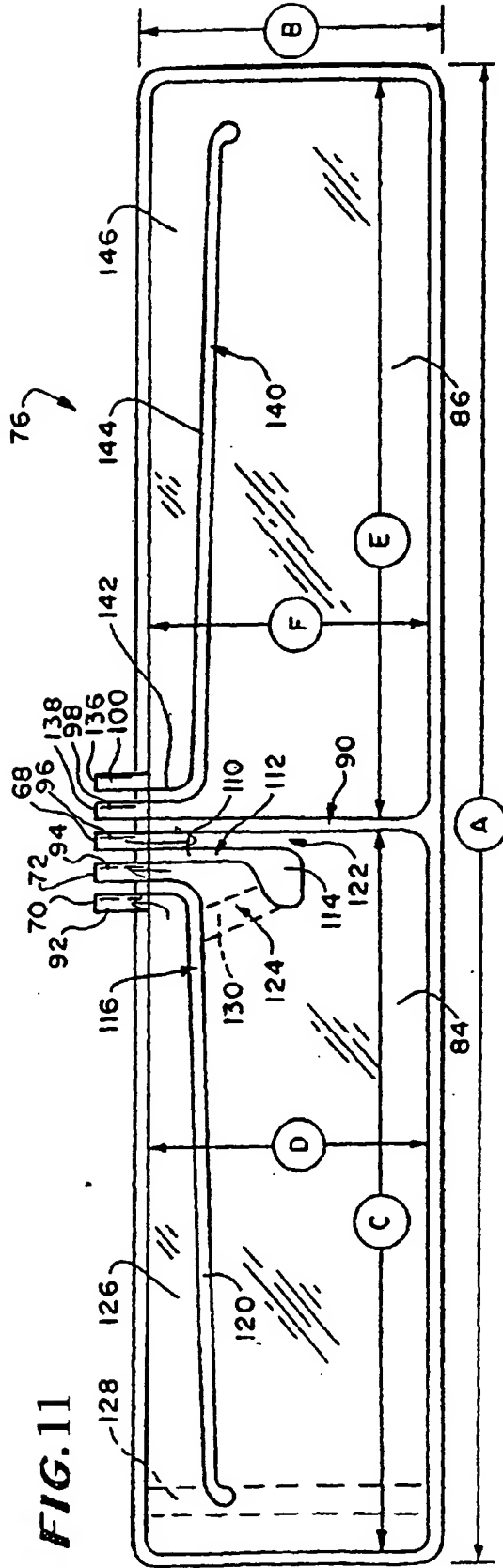
**FIG. 7**  
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**FIG. 8**  
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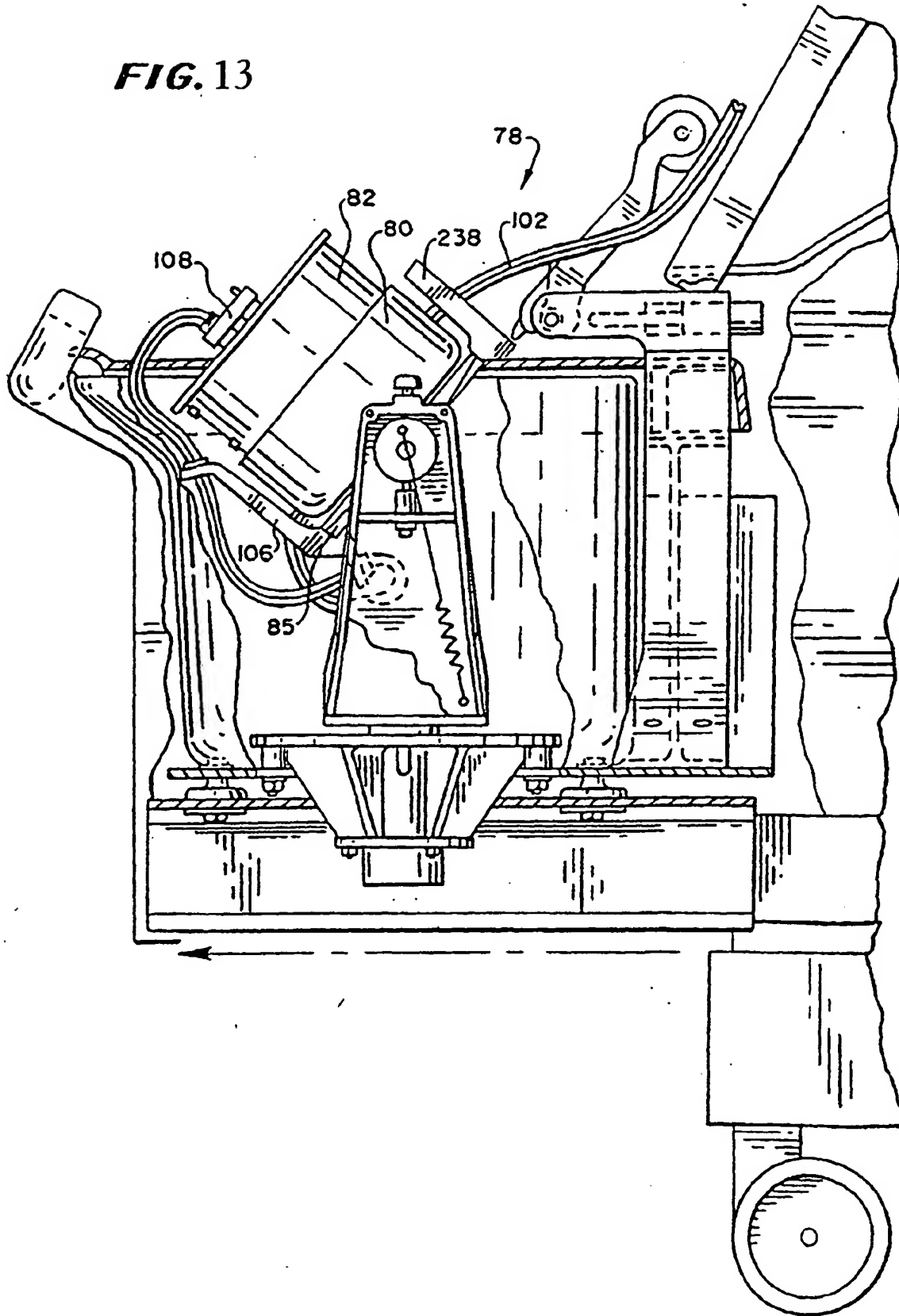




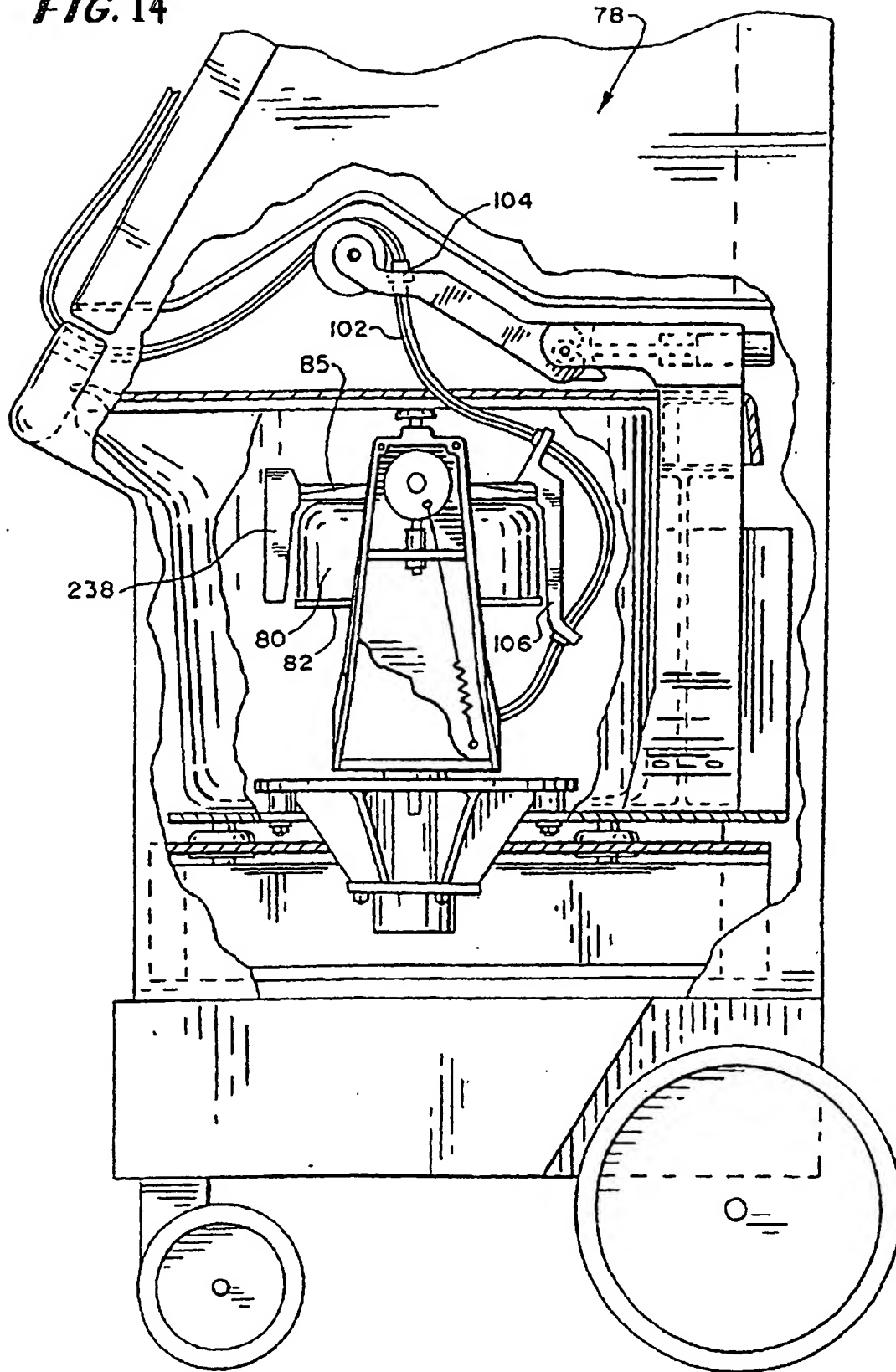




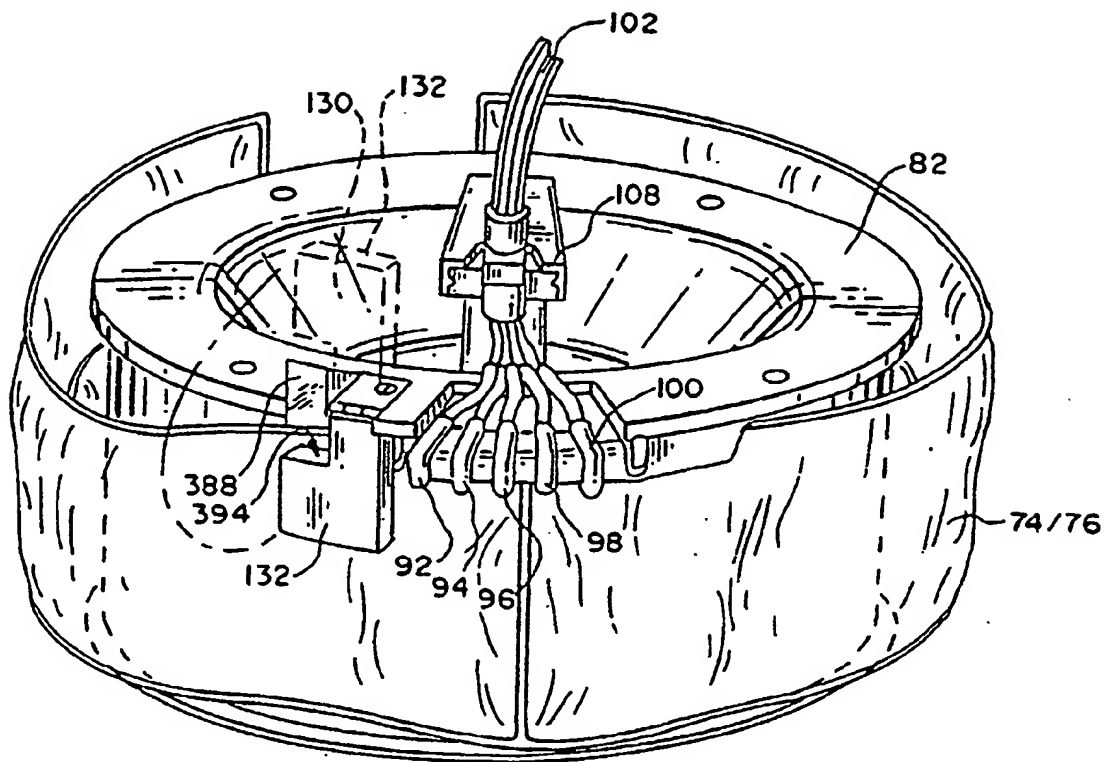
**FIG. 13**



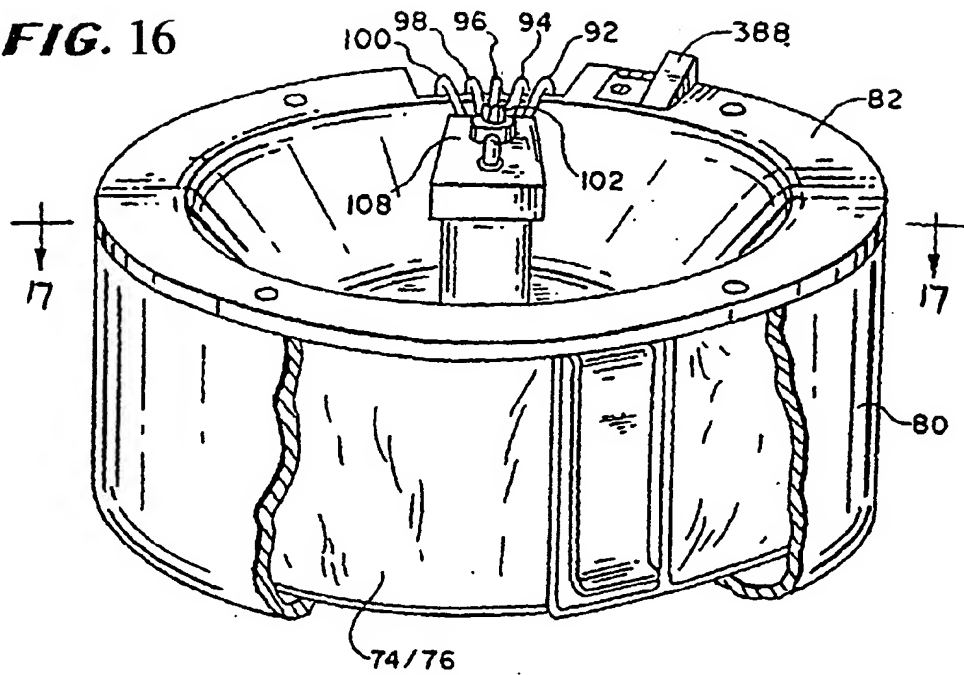
**FIG. 14**



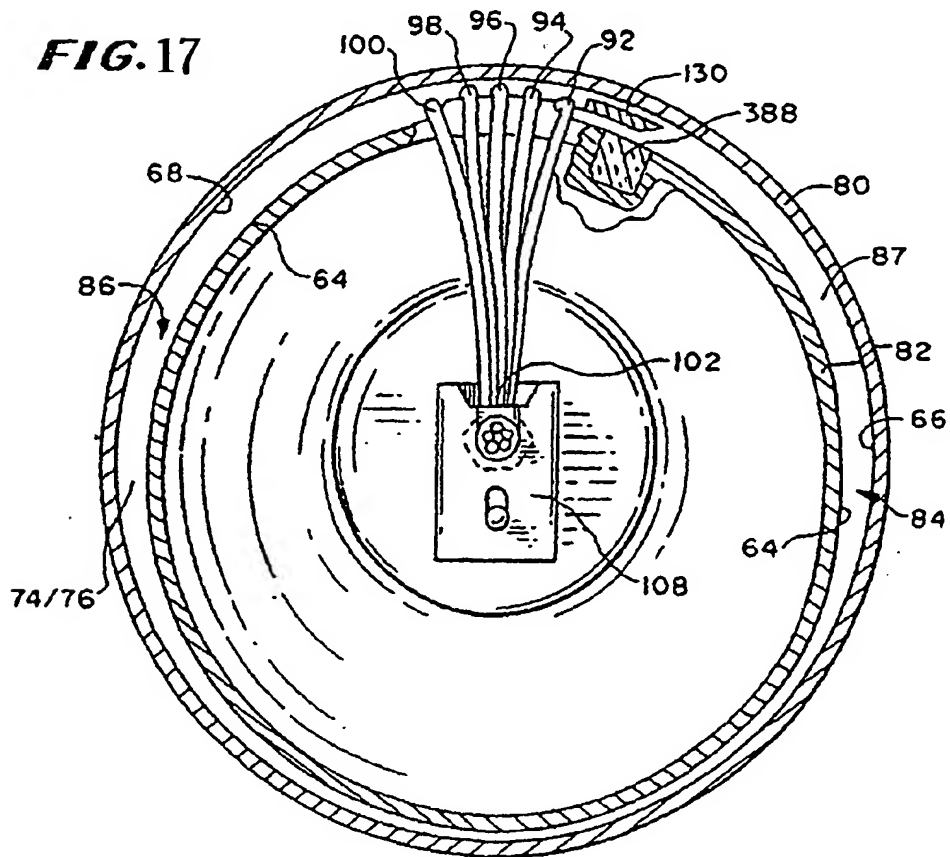
**FIG. 15**



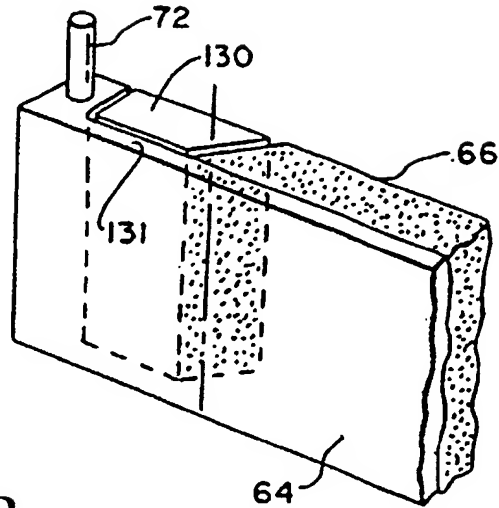
**FIG. 16**



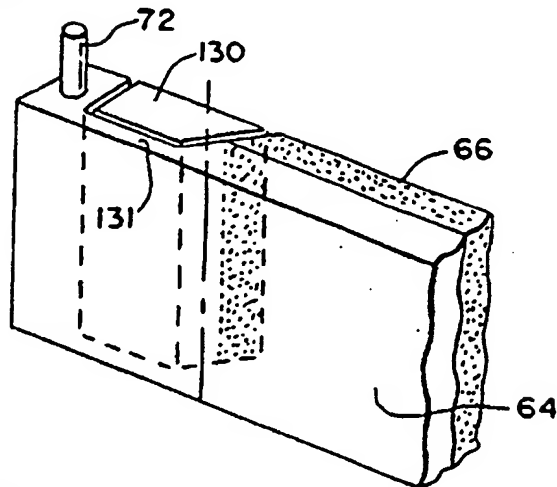
**FIG. 17**



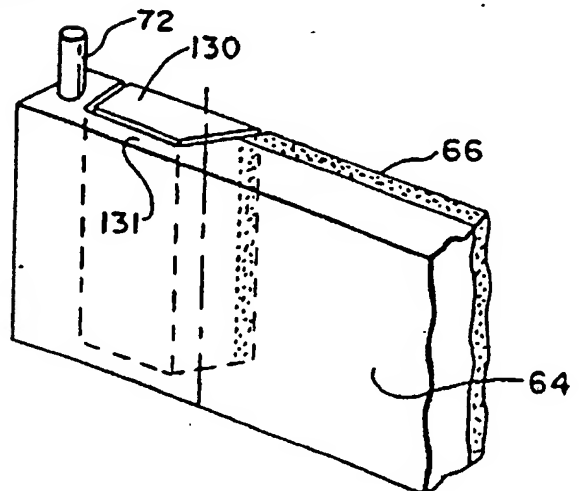
**FIG. 18A**



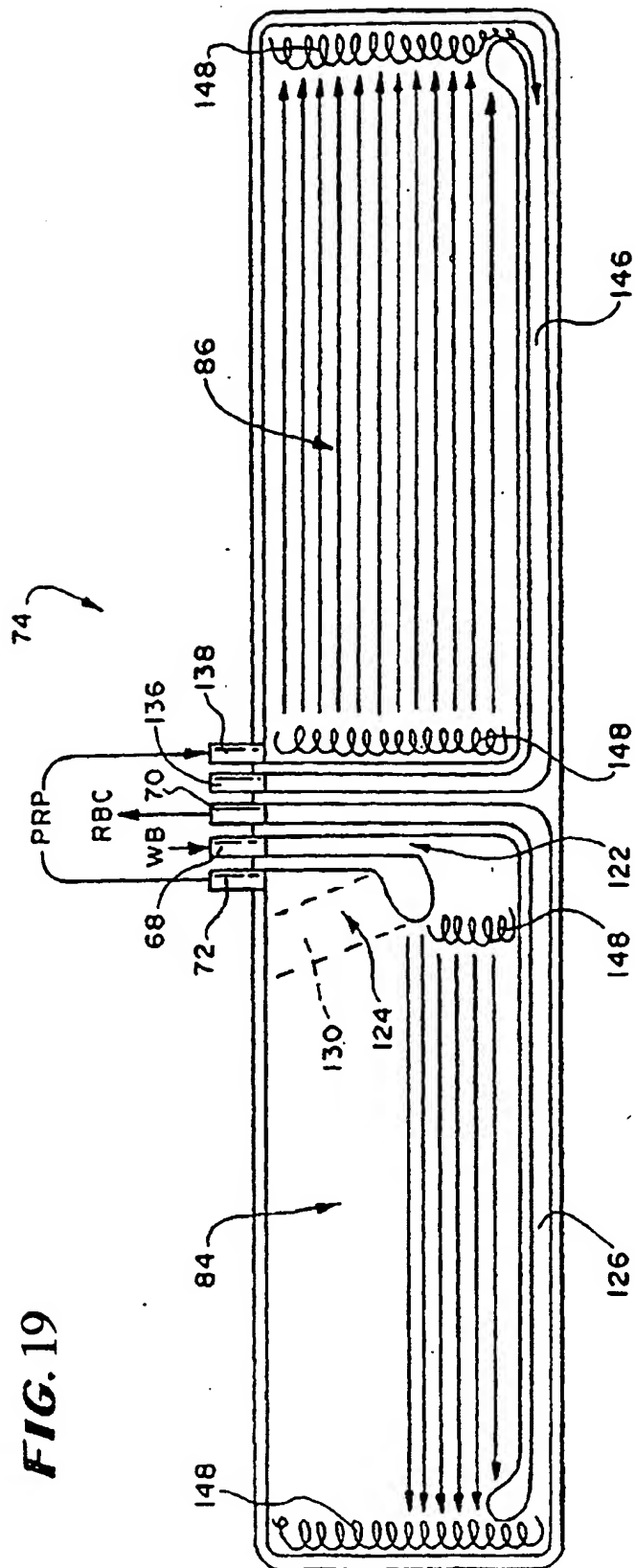
**FIG. 18B**



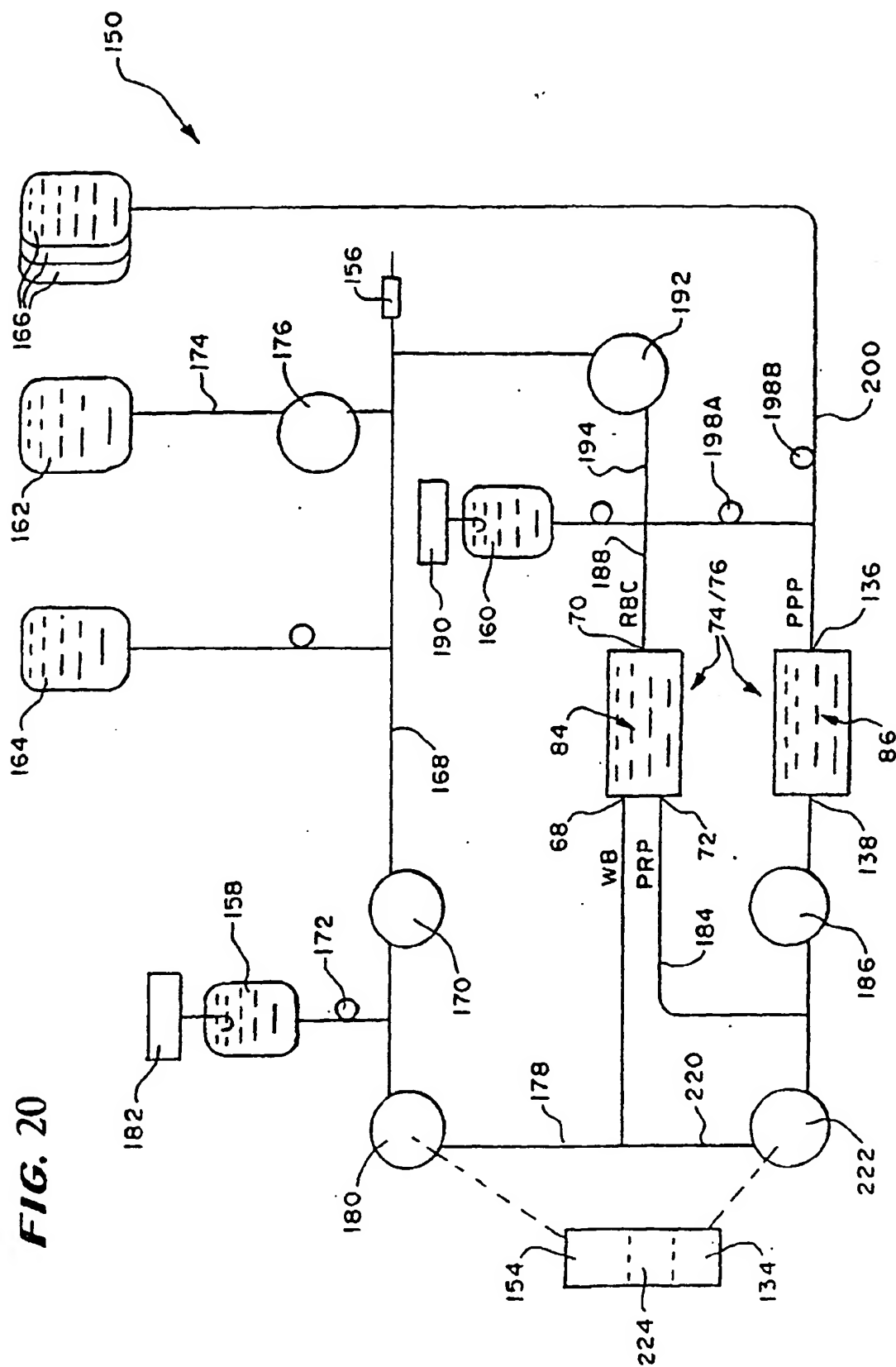
**FIG. 18C**



**FIG. 19**

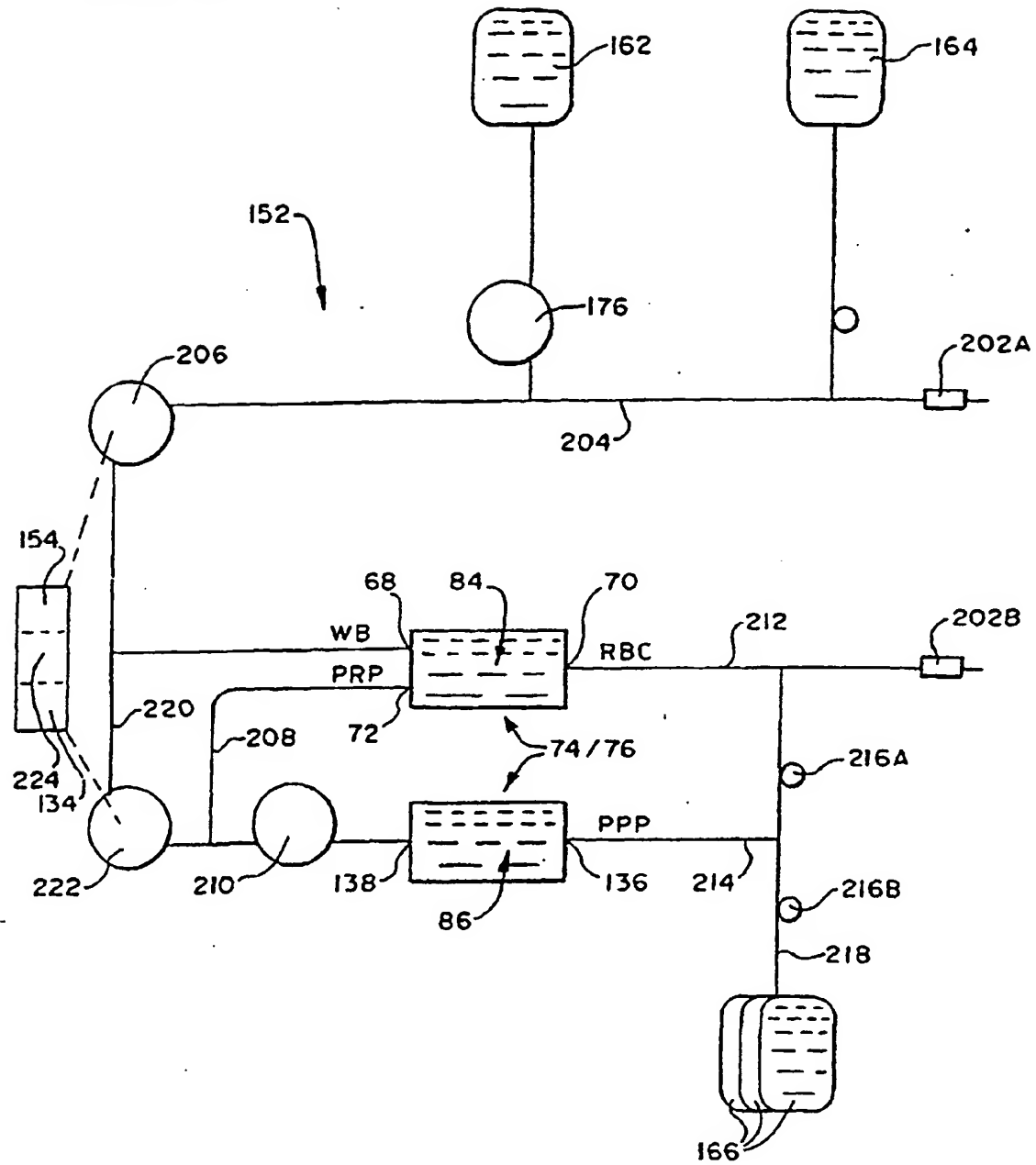


**FIG. 20**

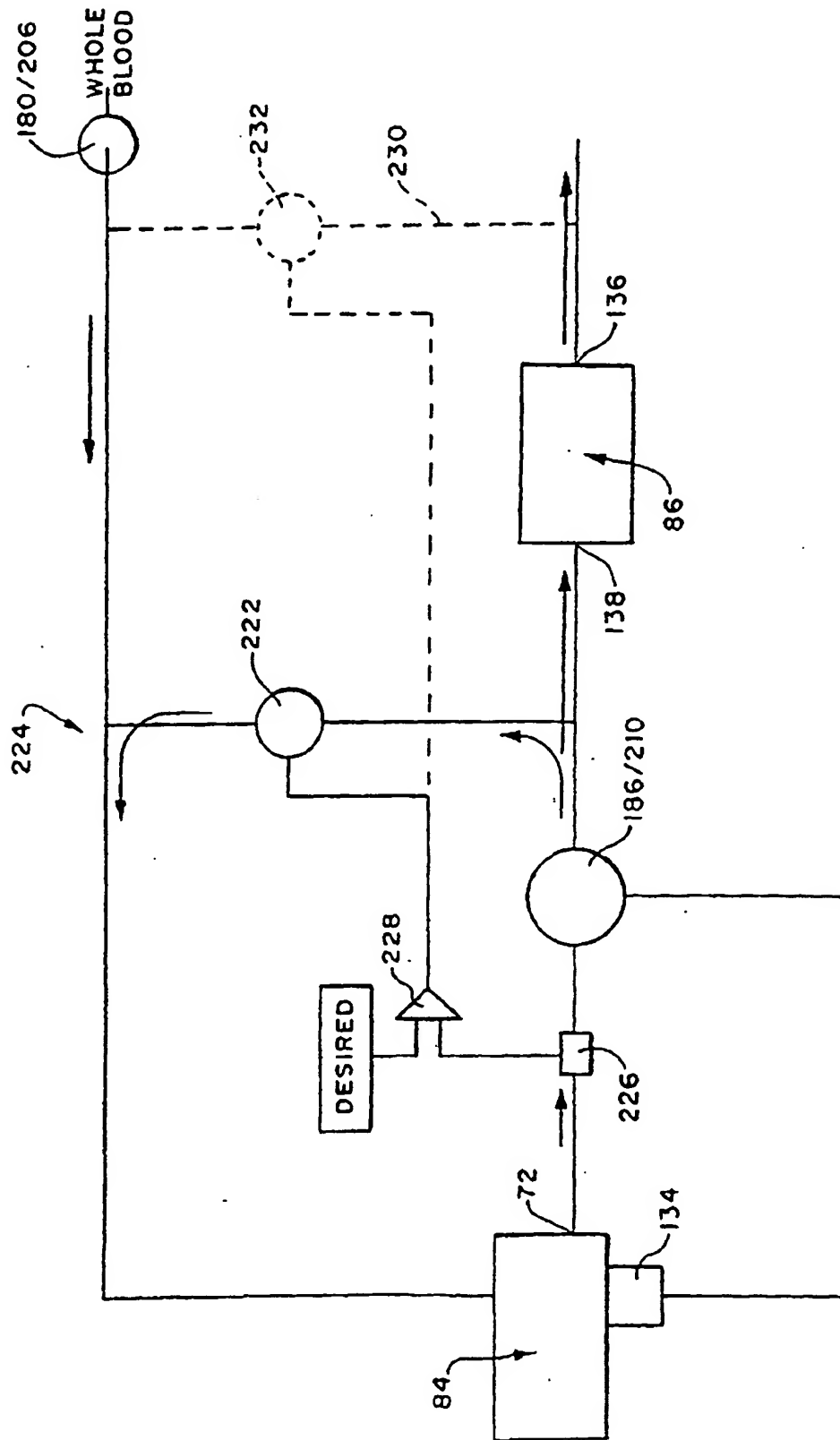




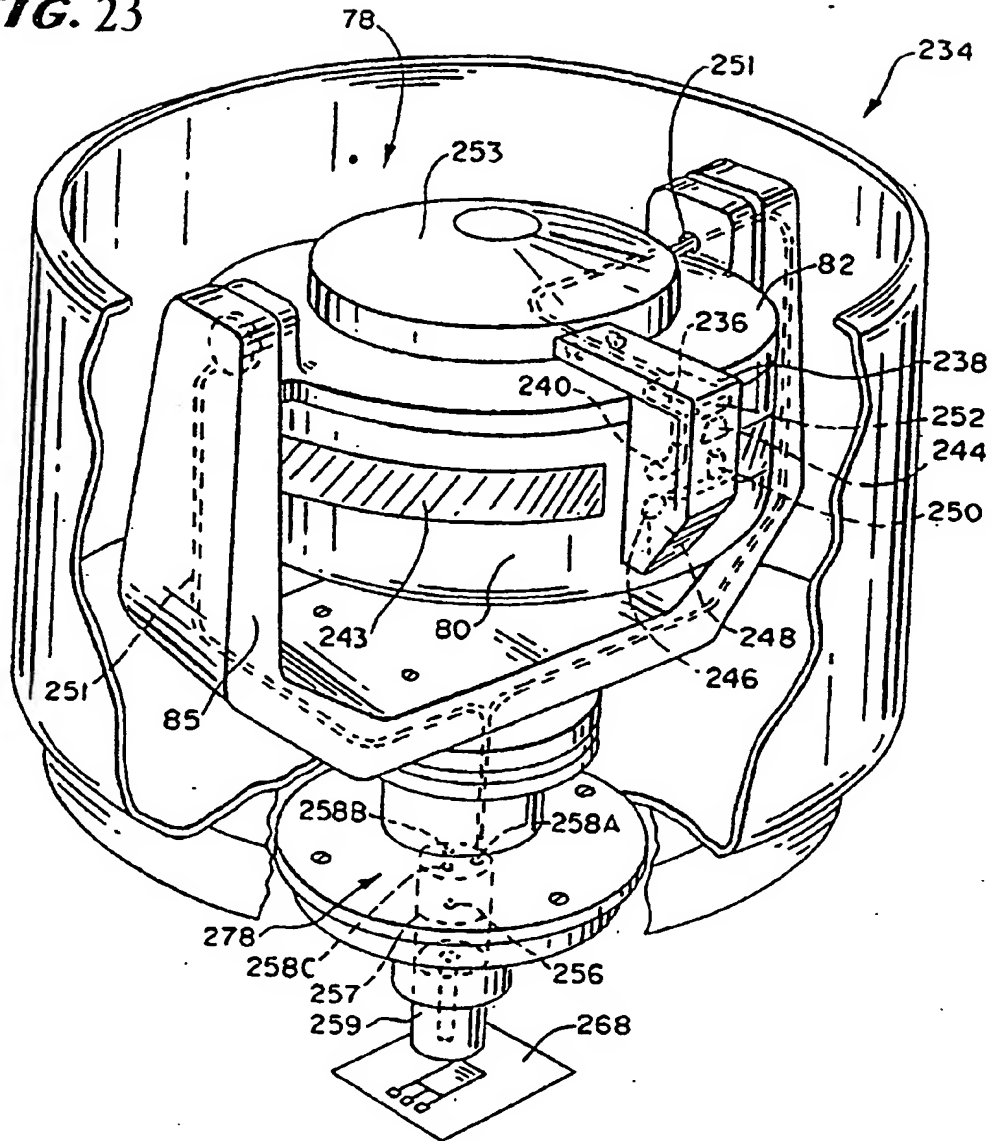
**FIG. 21**



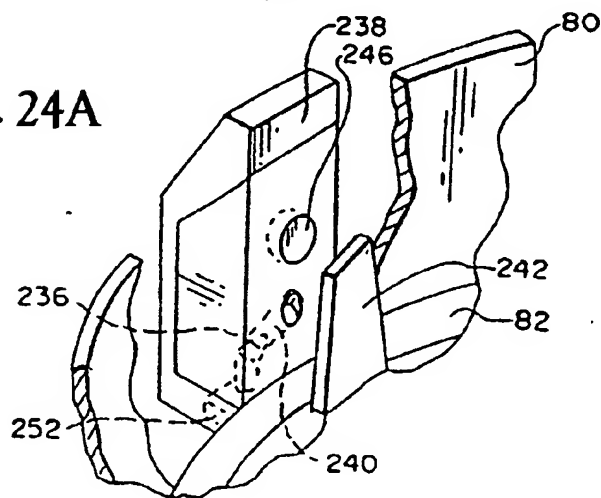
**FIG. 22**

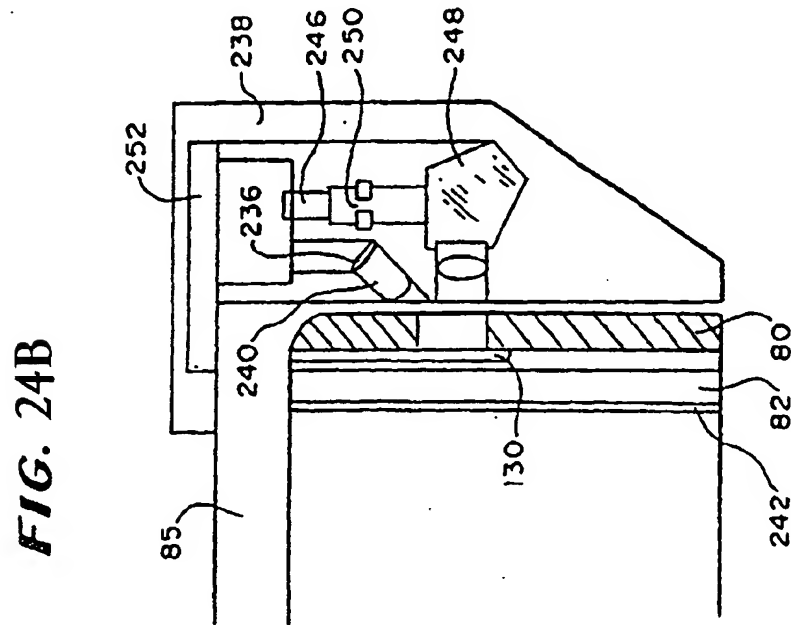
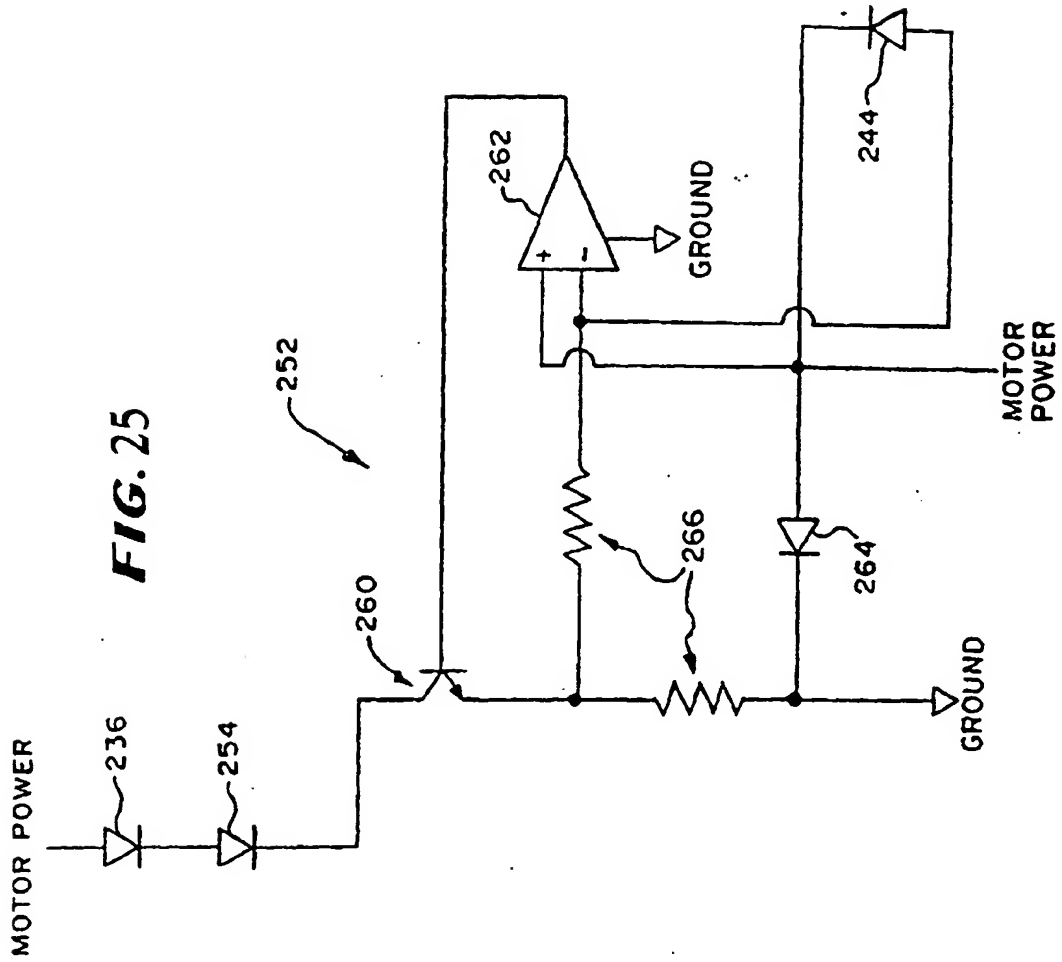


**FIG. 23**



**FIG. 24A**





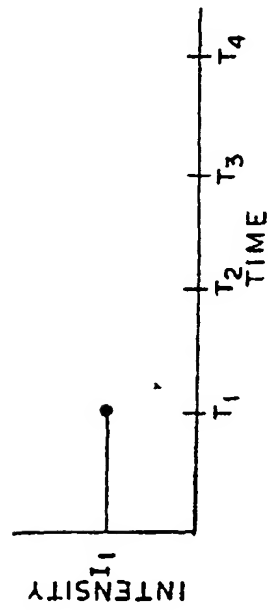
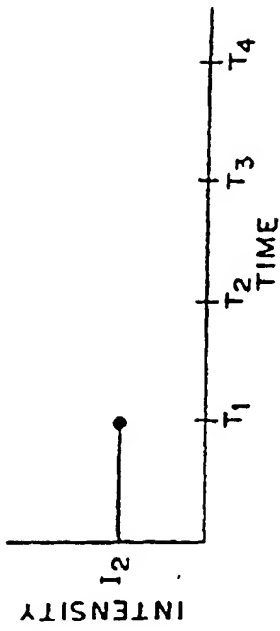


FIG. 26A

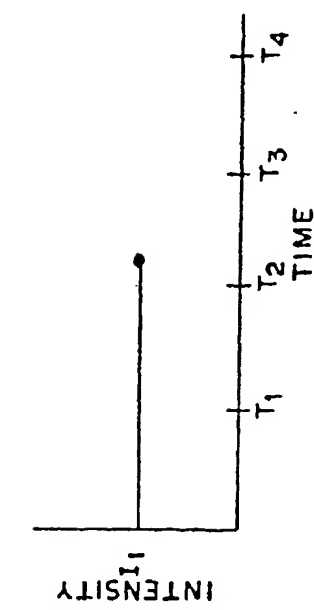
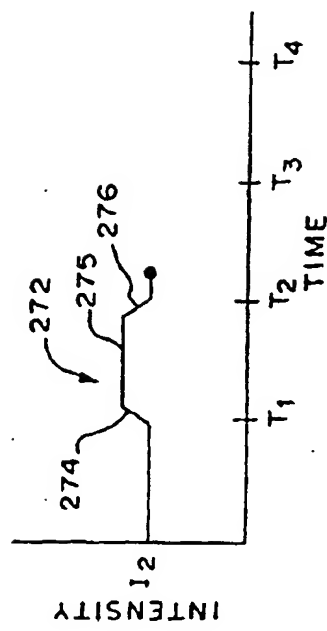


FIG. 26B

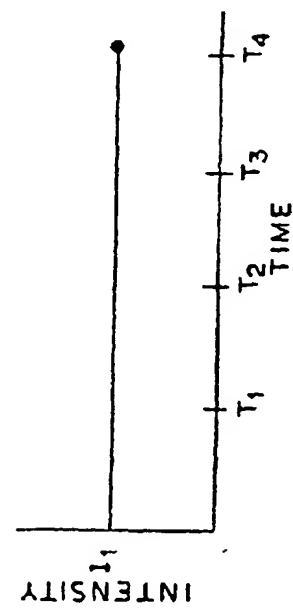
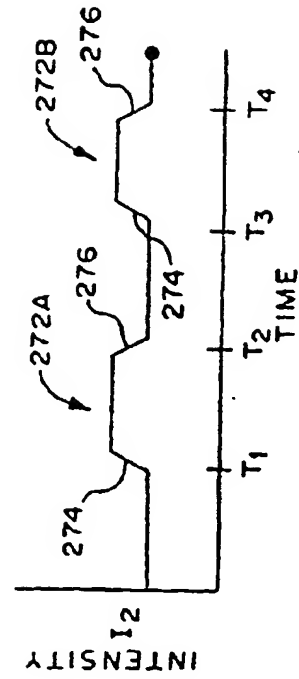
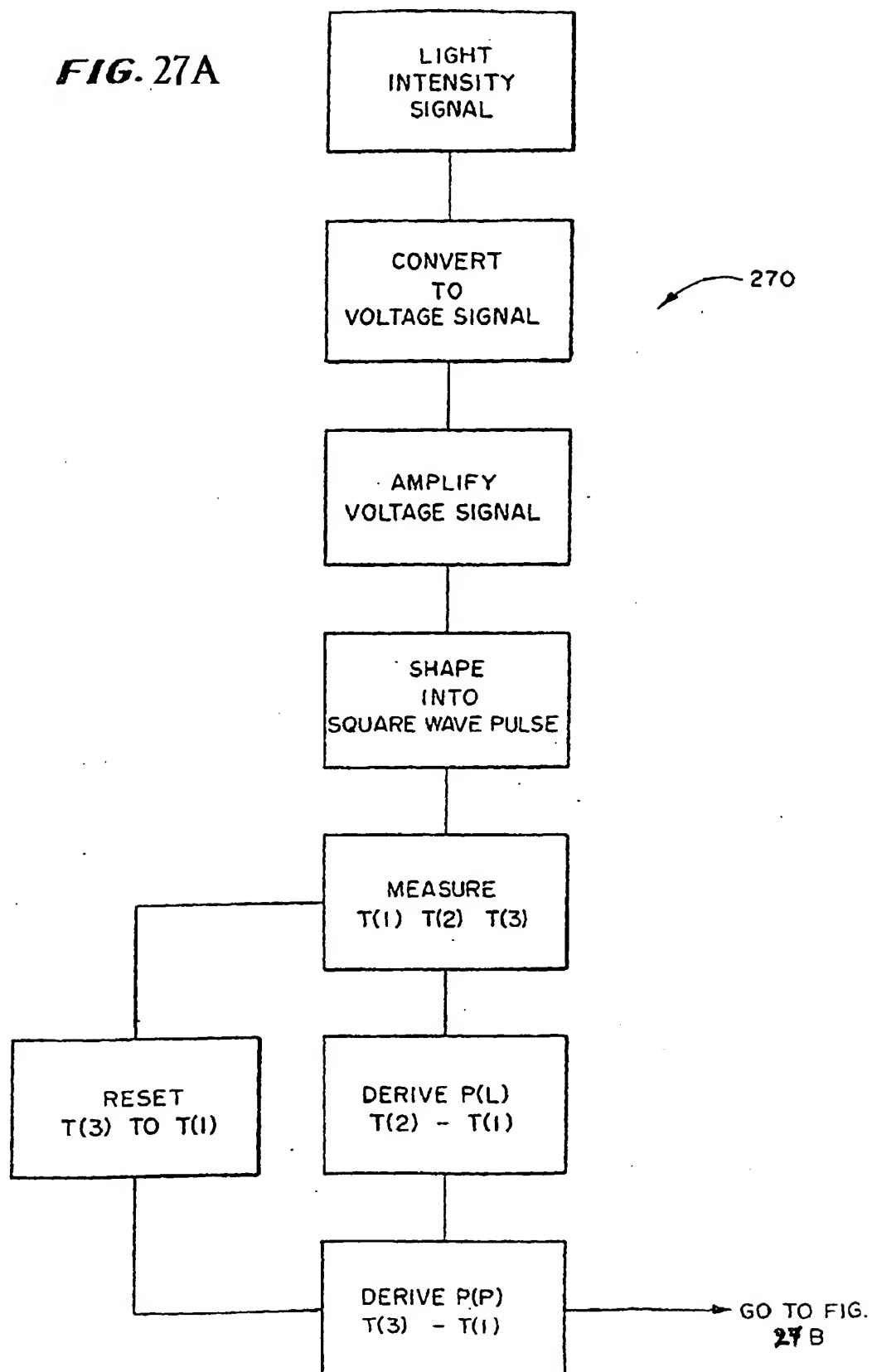
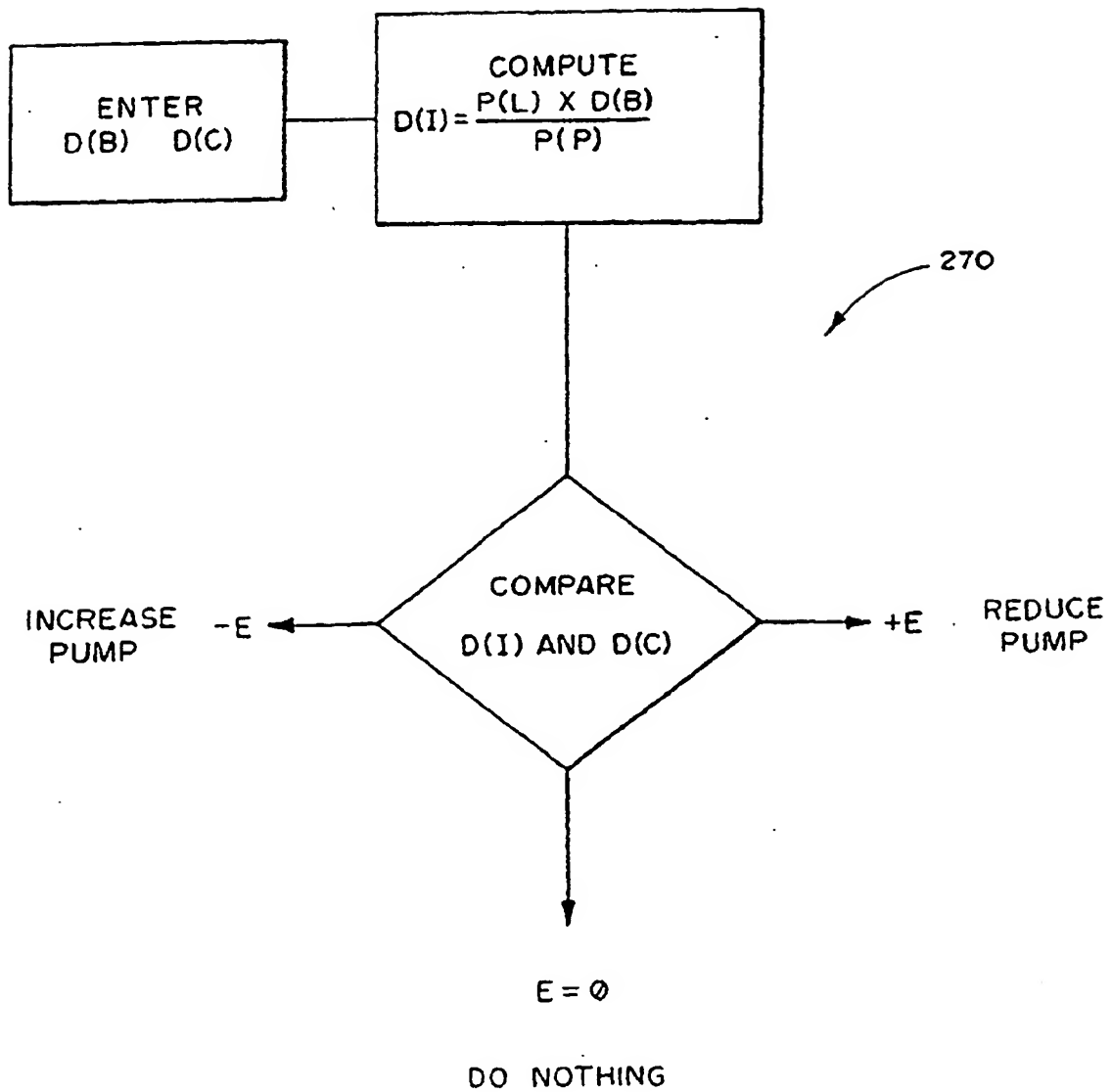
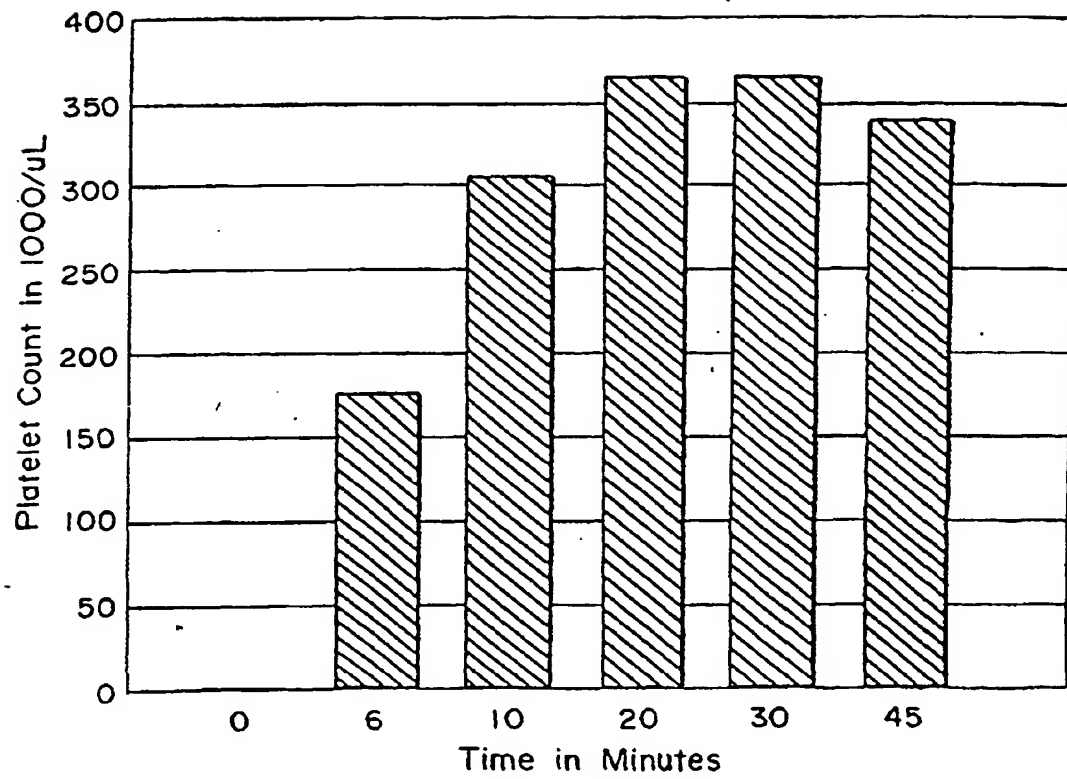


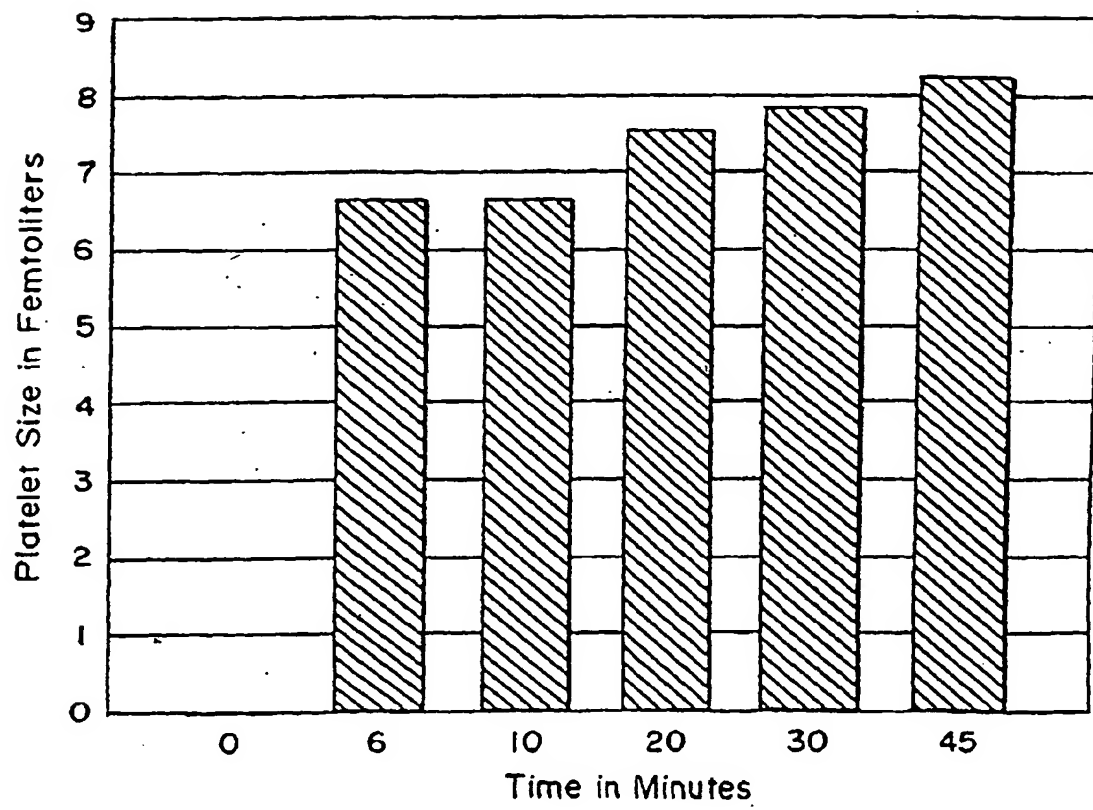
FIG. 26C

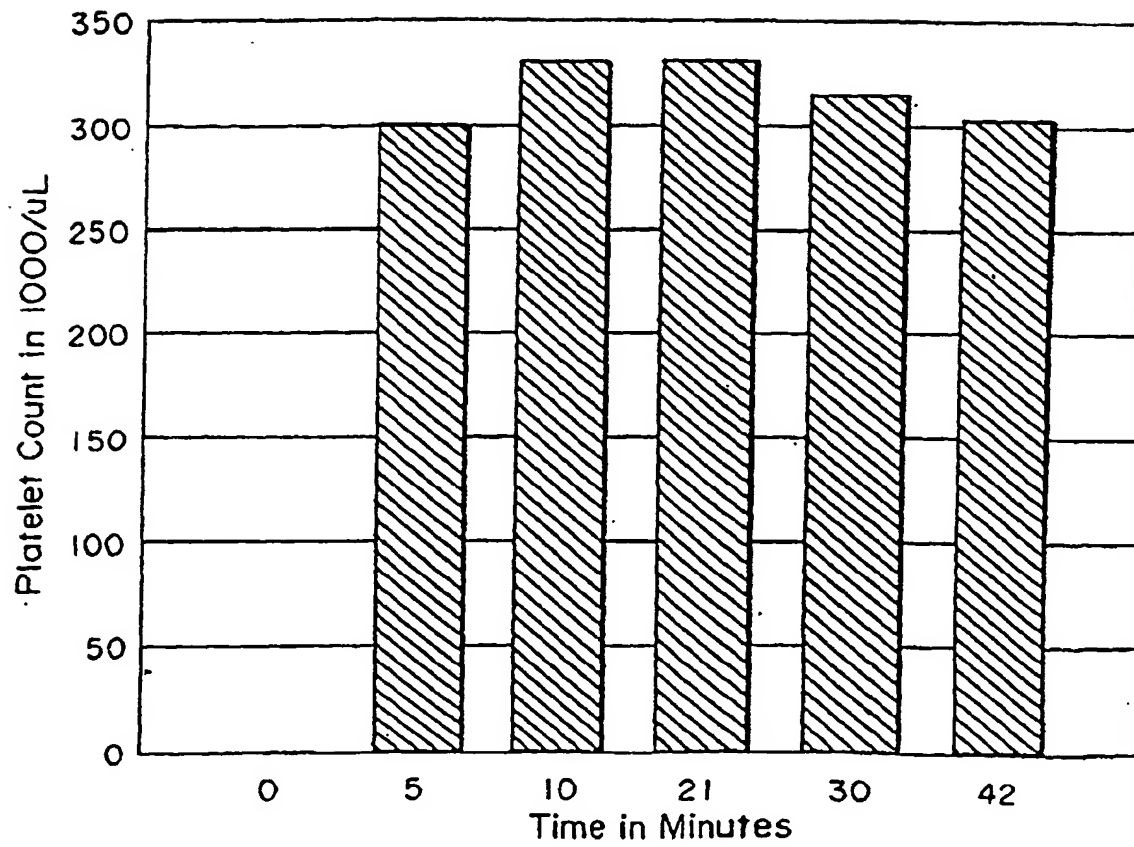
**FIG. 27A**

**FIG. 27B**

**FIG. 28A**



**FIG. 28B**

**FIG. 29A**

**FIG. 29B**